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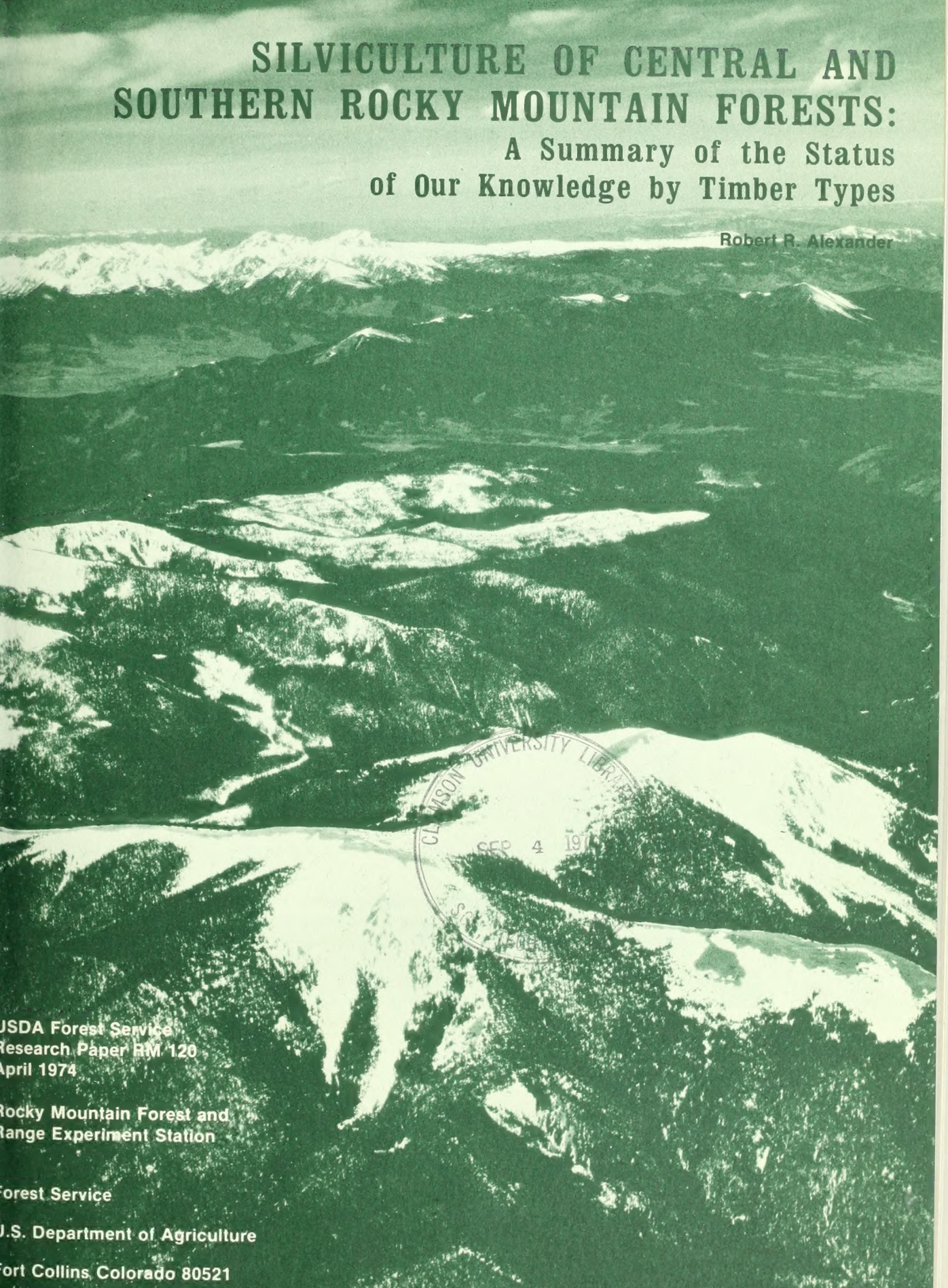
SILVICULTURE OF CENTRAL AND SOUTHERN ROCKY MOUNTAIN FORESTS:

A Summary of the Status of Our Knowledge by Timber Types

Robert R. Alexander



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USDA Forest Service
Research Paper RM 120
April 1974

Rocky Mountain Forest and
Range Experiment Station

Forest Service

U.S. Department of Agriculture

Fort Collins, Colorado 80521

ABSTRACT

Summarizes a series of comprehensive reports on the silviculture of lodgepole pine, ponderosa pine, mixed conifer, and spruce-fir timber types. Includes what is known, what can be recommended, and what additional information is needed for each timber type.

Oxford: 614. **Keywords:** Silviculture; forest regeneration; growth-yield; *Abies lasiocarpa, A. lasiocarpa* var. *arizonica, A. concolor; Picea engelmannii, P. pungens; Pinus contorta, P. ponderosa, P. strobiformis; Populus tremuloides.*

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USDA Forest Service
Research Paper RM-120

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A Summary of the Status of Our Knowledge by Timber Types

Robert R. Alexander, Principal Silviculturist

Rocky Mountain Forest and Range Experiment Station[1]

[1] *Central headquarters is maintained in cooperation with Colorado State University, Fort Collins.*

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PREFACE

Comprehensive reports of the status of our knowledge in timber management, applicable to the important central and southern Rocky Mountain forest types, have been prepared as Research Papers by the Rocky Mountain Forest and Range Experiment Station. These include:

"Silviculture of Subalpine Forests in the Central and Southern Rocky Mountains," by Robert R. Alexander, (RM-121),
"Silviculture of Southwestern Mixed Conifers and Aspen," by John R. Jones, (RM-122),
"Silviculture of Southwestern Ponderosa Pine," by Gilbert H. Schubert, (RM-123), and
"Silviculture of Ponderosa Pine in the Black Hills," by Charles E. Boldt and James L. Van Deusen (RM-124).

These papers have been condensed in this report to provide a general summary of the current status of our knowledge for all forest types in the central and southern Rocky Mountains. Acknowledgments and literature cited are included in the full-length papers.

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SILVICULTURE OF CENTRAL AND SOUTHERN ROCKY MOUNTAIN FORESTS:

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INTRODUCTION

Management goals for timber production and other forest uses are met through manipulation of forest cover. The degree of success depends on how well management decisions conform to the inherent characteristics of a particular species, existing stand conditions, and the environment, all of which affect the ability of a tree species to reproduce, survive, and grow. Since inherent characteristics are relatively unchangeable limitations, the resource manager must be certain that existing stand conditions and environmental factors are not altered by cultural practices to the extent that inherent species limitations are exceeded.

Although not all limiting factors and optimum conditions have been identified for tree species in the central and southern Rocky Mountains, Timber Management Research has been gathering data and providing forest managers with ecological and silvicultural information important to the management of commercial forest tree species for the past 60 or more years. A few summary publications on regeneration, silvics, silviculture, and management have been prepared for individual species, but most research results and observations have been presented as individual articles, papers, and notes in a variety of publications. Furthermore, some of what has been learned incidental to studies or from observations has never been fully documented. It is desirable therefore, for the research silviculturist to periodically pull together and organize all information which is scattered in various publications, as well as unpublished information, and make this knowledge available to the forest manager in one source.

The detailed status of knowledge summaries prepared for each forest type are intended to guide professional foresters and land managers responsible for supervising the application of silvicultural treatments by providing information on (1) what is known about the principal tree species, and (2) how this knowledge can be applied in the field to meet management objectives. Spinoff benefits include intensive literature reviews and the identification of knowledge gaps where additional research is needed.

The purpose of this document is to provide a general overview and evaluation of the more detailed reports. The forests of the central and southern Rocky Mountains are too extensive and complex, and the status of current knowledge and management practices too varied, to be handled as a homogeneous unit. Therefore, this Paper has been subdivided into five main sections: The Spruce-Fir Type, The Lodgepole Pine Type, Southwestern Mixed Conifer Forests — Including Aspen, The Southwestern Ponderosa Pine Type, and Black Hills Ponderosa Pine Forests. A discussion of timber resource priority problems is also included. Literature reviewed is not cited in this summary Paper, but is included in each of the four detailed reports as listed in the Preface (spruce-fir and lodgepole pine are combined in one report on subalpine forests).

THE SPRUCE-FIR TYPE

Engelmann spruce-subalpine fir forests occupy the highest forest environment in Wyoming, Colorado, and northern New Mexico (fig. 1). Spruce and fir are the principal species above 9,000 feet elevation on north-facing slopes, and above 10,000 feet on all other aspects. These forests are the largest and most valuable timber resource in Colorado and Wyoming (table 1). They are less important in terms of total forest resources in New Mexico. One of the features of spruce-fir forests is the large proportion of area in sawtimber-sized stands (table 2).

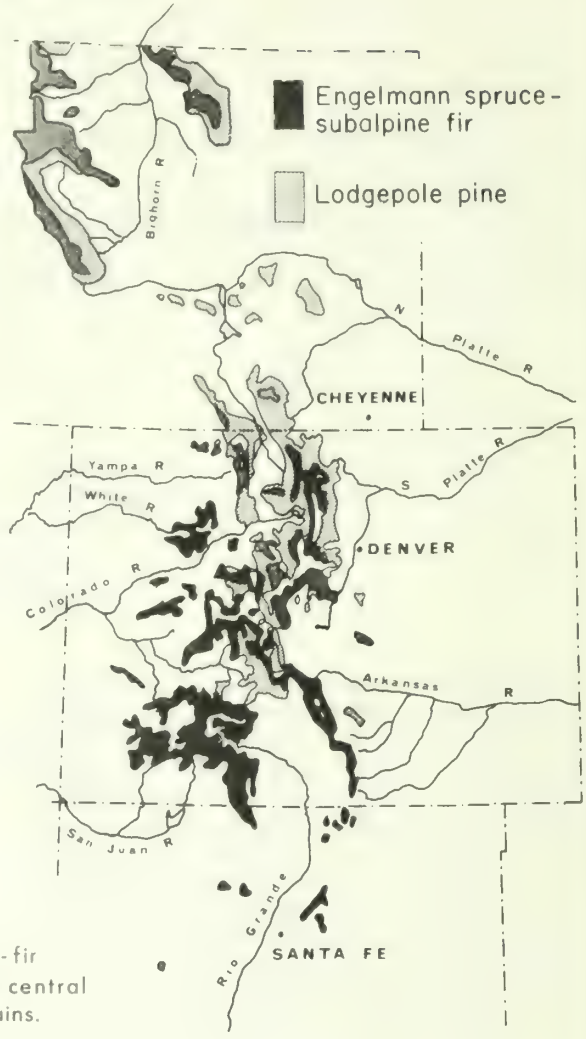

Figure 1.—Distribution of spruce-fir and lodgepole pine in the central and southern Rocky Mountains.

WHAT DO WE KNOW ABOUT SPRUCE-FIR FORESTS

Habitat Conditions

The climate of the spruce-fir zone is characterized by extremes that limit growth and reproduction. It is cool and humid, with long cold winters and short cool summers. Mean annual temperature is below 35° F, and frost can occur any month of the year. Precipitation, largely snowfall, is usually greater than 25 inches annually. Winds are predominantly from the west, and may be highly destructive.

Soils in the spruce-fir zone are young and complex. Soil parent materials vary according to the character of the bedrock from which they originated. Crystalline granitic rocks predom-

Table 1.--Acreage and volume (International 1/4-inch log scale) of sawtimber on commercial forests in the central and southern Rocky Mountains, by species and States

Species	Colorado		Wyoming		New Mexico		Arizona		South Dakota	
	M acres	*MM bm*	*M acres*	*MM bm*	*M acres*	*MM bm*	*M acres*	*MM bm*	*M acres*	*MM bm*
Engelmann spruce and true firs	3,393	33,260	847	9,541	525	5,257	110	2,147	0	0
Ponderosa pine	2.347	3,783	992	2,072	4,334	16,188	3,658	22,883	1,330	3,268
Douglas-fir	1,451	5,411	701	3,566	1,000	5,025	130	1,476	0	0
Lodgepole pine	2.068	6,024	1,802	5,798	0	0	0	0	--	--
White pines	139	472	166	1,256	43	640	--	186	--	--
White spruce	0	0	--	13	0	0	0	0	23	201
Aspen	2,794	3,482	320	159	367	1,233	79	259	0	0
Total	12,275	52,731	4,853	22,632	6,269	28,343	3,977	26,951	1,534	3,716

Table 2.--Percentage of commercial forest land area in the central and southern Rocky Mountains, by species, stocking classes, and States

Species and stocking class	Colorado	Wyoming	New Mexico	Arizona	South Dakota
Engelmann spruce and true firs:					
Sawtimber	81	82	85	100	0
Poletimber	14	14	5	--	0
Seedlings and saplings	1	1.5	7.5	--	0
Nonstocked	4	2.5	2.5	--	0
Ponderosa pine:					
Sawtimber	64	73	90	95	53
Poletimber	23	20	3.5	2.5	41.5
Seedlings and saplings	1	3	2	1	4.5
Nonstocked	12	4	4.5	1.5	1
Douglas-fir:					
Sawtimber	72	72	90	100	0
Poletimber	27	22	8.5	--	0
Seedlings and saplings	0.5	3	--	--	0
Nonstocked	0.5	3	1.5	--	0
Lodgepole pine:					
Sawtimber	34	47	0	0	0
Poletimber	60	45	0	0	0
Seedlings and saplings	5	6.5	0	0	0
Nonstocked	1	1.5	0	0	0
White pines:					
Sawtimber	45	46	100	0	0
Poletimber	52	44	--	0	0
Seedlings and saplings	2	6	--	0	0
Nonstocked	1	4	--	0	0
White spruce:					
Sawtimber	--	100	0	0	100
Poletimber	--	--	0	0	--
Seedlings and saplings	--	--	0	0	--
Nonstocked	--	--	0	0	--
Aspen:					
Sawtimber	7	18	49	44.5	0
Poletimber	80	57	43.5	49.5	0
Seedlings and saplings	13	16	7.5	6	0
Nonstocked	--	--	--	--	0

inate, but sedimentary, and basaltic and acidic volcanic rocks commonly occur. Most valleys have been glaciated and glacial deposits are common.

Climax and Succession

Spruce-fir forests are considered the climax forests where they grow in the central and southern Rocky Mountains. Climax forests are not easily displaced by other vegetation, but complete removal of a spruce-fir stand by fire or logging results in such a drastic environmental change that spruce and fir are usually replaced by lodgepole pine, aspen, or shrub and grass communities. The kind of vegetation initially occupying the site usually determines the length of time required to return to spruce-fir forests (fig. 2).

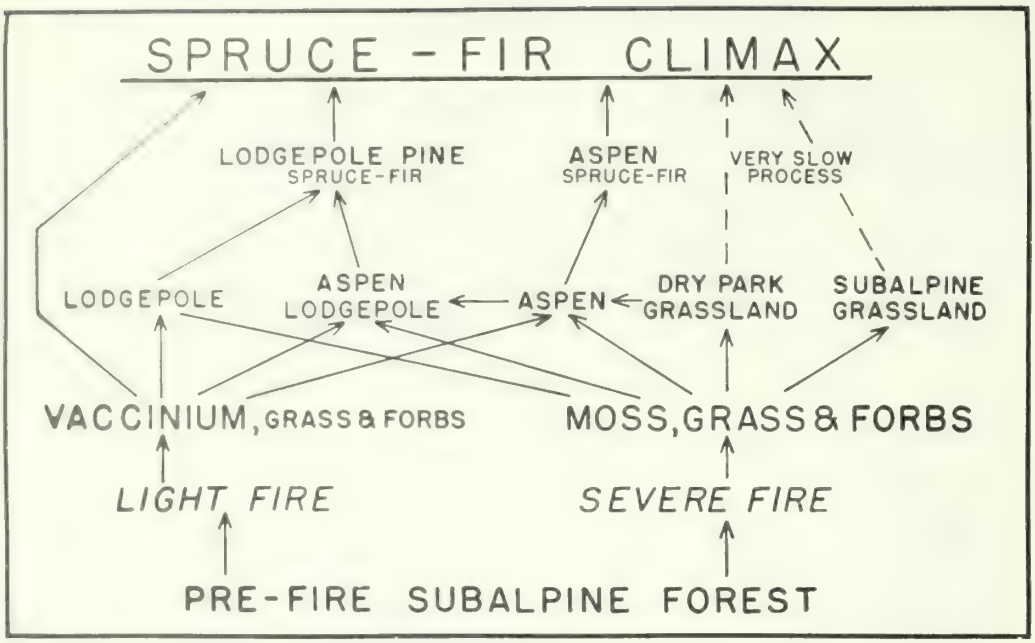

Figure 2.—Succession in subalpine forests after fire.

Stand Conditions

Old-growth spruce-fir forests grow on a wide range of sites with a great diversity of stand conditions and characteristics. This diversity complicates the development of silvicultural systems needed to convert old-growth to managed stands for a variety of uses. Some stands are single-storied, indicating that spruce-fir can be grown under even-aged management. Others are two-, three-,and multi-storied stands. These latter stands frequently have a manageable stand of advanced growth. Associated understory plant communities are also diverse. The distinctive overstory-understory combinations or habitat types each have a distinctive ecology and management potential.

The composition of spruce-fir forests varies considerably with elevation. At high elevations, spruce may form nearly pure stands while at mid elevations spruce usually predominates in the overstory and fir in the understory. At lower elevations where the sites are drier, the ratio of spruce to fir may be low and lodgepole pine may replace spruce in the overstory. Aspen is also a common associate at mid to lower elevations.

Damaging Agents

Windfall, a common cause of mortality in old-growth spruce-fir stands, limits the way stands can be handled (fig. 3). Partial cutting

Figure 3.—Spruce-fir blowdown in an uncut stand. San Juan National Forest, Colorado.

increases the risk of windfall because the entire stand is opened up. Less damage is usually associated with clearcutting because only the boundaries between cut and leave areas are vulnerable. Susceptibility to windthrow is also related to topographic exposure, soil depth and drainage, and age, soundness, size, and stand density.

The spruce beetle is the most serious insect pest of spruce-fir forests, and it limits the options open to the manager. Overmature spruces are attacked first, but if the infestation persists, beetles will attack smaller trees after the larger trees are killed. Epidemic attacks usually have been associated with extensive windthrow where down trees have provided an ample food supply needed for a rapid buildup of beetle populations. Cull material left after logging also has started outbreaks. Felling and salvaging attacked or the larger susceptible, overmature trees, and disposing of green cull material, are the most effective silvicultural controls, especially in stands with a good stocking of trees in the smaller diameter classes.

The most common diseases in spruce-fir stands are caused by wood-rotting fungi and broom rusts. They result in loss of volume and reduced growth, and predispose trees to windthrow and windbreak.

Natural Reproduction and Early Survival

Engelmann spruce reproduces almost entirely from seed. It is only a moderate seed producer, and crops vary from year to year. Infrequent seed crops mean that natural reproduction cannot be expected every year. Spruce seed is light and is dispersed by wind and gravity. Seedfall diminishes rapidly as distance from source increases, with about half of the seed falling within five to six times tree height. This rapid decrease limits the size of opening that will restock to natural reproduction.

Seed sources available for natural reproduction include (1) trees left around the perimeter of cleared openings, (2) residual trees left on the cut area, and (3) seed produced by trees cut on the area. One of the significant considerations in leaving a seed source is the capability of the trees in the residual stand to produce seed. Another consideration is resistance to windthrow.

Viable seeds that survive overwinter normally germinate in early summer following snowmelt. In the undisturbed forest, spruce germinates and becomes established on a variety of seedbeds. Removal of part or all of the overstory produces new microenvironments, some of which are unfavorable to germination and initial survival. Seedbed preparation is one way to modify limiting factors sufficiently to enable seedlings to become established.

Spruce germination and initial survival are usually better on exposed mineral soil and mineral soil with incorporated organic matter than other seedbed types. The natural forest floor, duff, litter and undecomposed humus, decayed wood, and burned areas are generally poor seedbeds even when moist, because either seeds cannot absorb sufficient water to germinate or the rate of seedling root growth is too slow to keep up with the rate of drying.

Engelmann spruce is restricted to high elevations because of low tolerance to high temperatures, but light intensity and total solar radiation are high where spruce grows. Light is essential to seedling survival, but spruce does not establish readily in the open at high elevations. High light intensity is one of the factors contributing to mortality. Solar radiation at high elevations also heats exposed soil surfaces and increases water losses from both seedlings and soil, especially during periods of clear weather in years when precipitation during the growing season is low or irregular. Few seeds can imbibe sufficient water to germinate, and most newly germinated seedlings are killed by drought or heat girdle. Shade reduces mortality from high light intensity, drought and heat girdling, and increases germination by reducing temperatures, thereby conserving moisture. However, low temperatures on shaded seedbeds in the spring following snowmelt may also delay germination so that, by the time seedbeds are warm enough, they are too dry.

Frost can occur any month where spruce grows. It is most likely to occur in depressions and cleared openings because of cold air drainage and radiation cooling (fig. 4). Newly germinated seedlings are especially susceptible to damage from early fall frosts. Older seedlings are most susceptible to frost early in the growing season when tissues are succulent. In the early fall, alternate freezing and thawing and saturated soils unprotected by snow cover are conducive to frost heaving. Shade reduces mortality by reducing loss of radiant energy from soil and seedlings.

Spruce regeneration success is also limited by biotic factors. Cone and seed insects and small mammals reduce available seed supply. Newly germinated seedlings are killed by damping-off fungi on all seedbed types if they remain damp for long periods of time. Snowmold fungi may damage or kill both natural and planted seedlings if they remain under the snow too long. Birds clip the seedcoats of newly

Figure 4.—Frost damage to an open-grown, planted Engelmann spruce seedling.

germinated seedlings, and voles and pocket gophers debark and kill established seedlings. Young seedlings are also vulnerable to trampling.

Spruce seedlings become established more readily on sites protected by such understory plants as willows, shrubby cinquefoil, fireweed, and dwarf whortleberry than in the open. These plants shade seedlings without seriously depleting soil moisture. In contrast, seedlings do not survive near clumps or scattered individual plants of grasses or sedges or herbaceous plants such as bluebells. Death is due to root competition for moisture, and smothering by cured vegetation compacted under dense snow cover.

Site Quality

Site index is the conventional method for estimating potential productivity. Such estimates are essential to the land manager as a means of identifying and intensifying management practices where timber production has the greatest potential. Curves of the height-age relationship of dominant spruce have been prepared that are suitable for estimating site index at base age 100 years in spruce-fir stands (fig. 5).

Frequently the conventional height-age method cannot be used to estimate site index because there are no trees present, or they are either too young or unsuitable for measurement. Site index for granitic soils in northern Colorado and southern Wyoming can be estimated using the depth of soil to the top of the C horizon and elevation in feet (fig. 6). This method is not suitable for other areas in the central and southern Rocky Mountains, however.

Growth and Yield

With the high proportion of spruce-fir still in old-growth stands, the forest manager must largely accept what nature has provided during the period of conversion to managed stands. Growth estimates based on Forest Survey inventories indicate that average annual growth over all sites in old-growth spruce-fir forests is only about 80 to 100 board feet (fbm) per acre.

As areas of old-growth spruce-fir are converted into new stands, they must be managed from the regeneration period to final harvest. The only growth prediction tool now available for spruce-fir stands in the central Rocky Mountains was developed 30 years ago for selectively cut stands, for sawtimber only, and for stand structures that are no longer management goals. Field data are now being collected in the central Rocky Mountains that will use established computer simulation procedures to develop yield tables for managed spruce-fir stands. The program produces a series of yield tables which show how projected growth will vary in response to changes in cultural treatments and/or variations in original stand and site conditions.

WHAT PRACTICES CAN WE NOW RECOMMEND

Regeneration Silviculture

The recognized harvest cutting methods applicable to spruce-fir forests include clearcutting, and shelterwood and selection cutting and their modifications. The choice of cutting method depends basically on management objectives and environmental considerations, but stand conditions, associated vegetation, and windfall and spruce beetle susceptibility — which vary from place to place on any area — impose limitations on how stands can be handled. For example, partial cutting should not be used in high wind risk situations or in stands where spruce beetle infestations are building up. Cutting to bring old-growth under management on many areas is likely to involve a combination of several partial cutting treatments, clearcutting, and sanitation salvage cutting. To restock these cutovers, managers should first consider the cultivation of existing **acceptable** advanced reproduction, and secondly, inducing subsequent restocking by natural or artificial means.

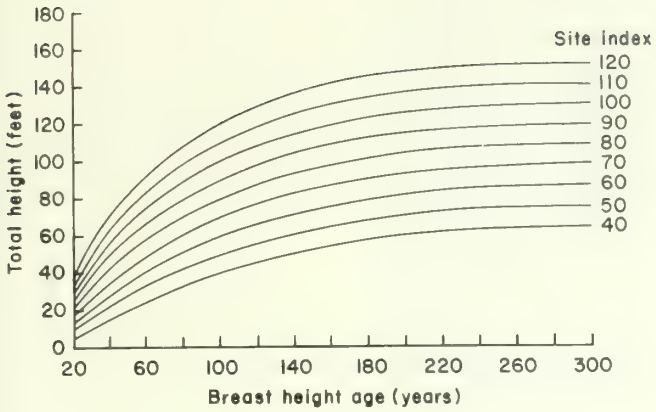

Figure 5.—Site index curves for Engelmann spruce in the central Rocky Mountains. Base age: 100 years, breast height.

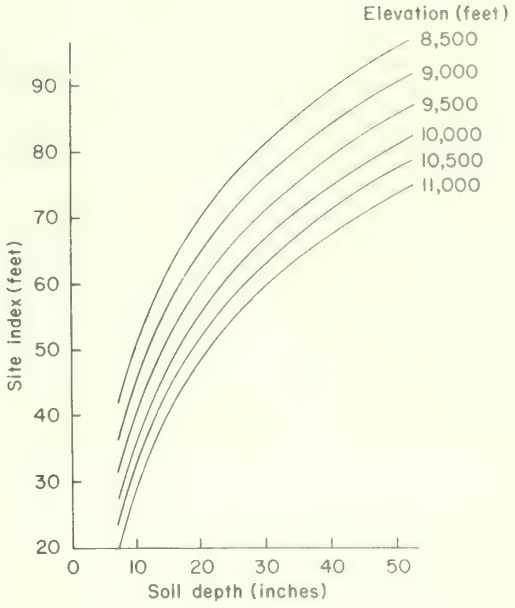

Figure 6.—Site index for Engelmann spruce on granitic soils in southern Wyoming and northern Colorado, determined from soil depth to the top of the C horizon and elevation.

Management With Advanced Reproduction

Many spruce-fir forests have an understory of advanced growth. However, because of variations in age, composition, quality, and quantity of advanced reproduction, its potential for future management must be carefully evaluated before harvesting begins. One course of action is followed if advanced reproduction is to be managed, another if it is not. Furthermore, the manager must reevaluate the stand after the final harvest and slash disposal to determine the need for supplemental stocking.

The size, shape, and arrangement of clearcut openings is not critical from a regeneration standpoint, but to be compatible with other key uses, openings should not be greater than about five to eight times tree height, irregular in shape, and blend into the landscape. The overstory will generally be removed in one step.

On partially cut areas, shelterwood cutting should be used where trees are uniformly spaced, and group selection where they are clumpy in single-, two-, and three-storied stands. The overstory will be removed in more than one step. An overwood removal in one or two steps is usually appropriate in multi-storied stands, while individual tree selection is appropriate in multiple-use areas where management objectives include maintenance of high forests. The amount of basal area that can be removed at each entry, the number of entries, and the size of group openings is determined by stand characteristics and windfall risk.

Protection of the residual stand — merchantable trees left after partial cutting, and advanced reproduction in both clearcutting and partial cutting — from logging damage at each cut is of primary concern (fig. 7). Protection begins with a well-designed logging plan at the time of the first cut. To minimize damage, skid roads must be laid out and marked on the ground, travel of skidding and other logging equipment restricted to the skid roads, and trees felled into openings as much as possible in a herringbone pattern that will permit logs to be pulled onto the skid roads with a minimum of disturbance.

Slash treatment after each cut should be confined to areas of heavy concentrations as required for protection from fire and insects or preservation of esthetic values. Slash must be treated carefully to avoid unnecessary damage to advanced reproduction and residual trees — if they are destroyed during slash disposal, care taken in logging is wasted.

Management With Reproduction After Cutting

On clearcut units, layout, logging plans, and slash disposal and seedbed treatment should be designed to facilitate seed dispersal, and to create favorable conditions for germination and seedling establishment. Clearcutting can be by patches, blocks, or strips. Requirements for seed

Figure 7.—Advanced spruce and fir reproduction after clearcutting and slash disposal. Fraser Experimental Forest, Colorado.

dispersal, site preparation, and aspect will influence the size of opening that will restock to natural regeneration. The cutting unit must be designed so that seed from the surrounding timber margin reaches all parts of the openings. Furthermore, cutting unit boundaries must be located where they will be most windfirm.

In general, clearcutting for natural regeneration is most likely to succeed on north and east aspects, providing the right combination of mineral soil and shade has been created, and openings are no larger than about five to six times tree height. If larger openings are cut, the area beyond effective seeding distance will have to be planted. Clearcutting on south and west aspects is not likely to result in an acceptable stand of new reproduction in a reasonable period of time without fill-in planting.

Slash disposal and seedbed preparation will be needed after clearcutting. If slash is concentrated for burning, the piles or windrows should be kept small or narrow, and cover a minimum proportion of the area. Mineral soil can be exposed by mechanically scarifying the ground surface, sometimes in connection with slash disposal or by broadcast burning. Careful mechanical scarification or broadcast burning will prepare a satisfactory seedbed if it exposes bare mineral soil and destroys some of the competing vegetation, but leaves shade protection. To provide adequate shade, it may be necessary to rearrange some of the residual slash and the true-fir cull material over 8 inches in diameter.

On partially cut areas to be regenerated by new reproduction, an overstory canopy or trees standing around the margins of small openings provide a seed source within effective seeding distance and an environment compatible with germination, initial survival, and seedling establishment. The manager must make sure, however, that a suitable seedbed is provided after the seed cut where shelterwood cutting is used, and after each cut where group selection is used. Some slash disposal will probably be needed after each cut, but it should be confined to concentrations and that needed to reduce visual impact because most equipment now available for slash disposal is not readily adaptable to working in shelterwood cuttings. Furthermore, burning of slash will cause additional damage to the residual stand. As much of the down sound dead and green cull material as possible should be skidded out for disposal at the landings or at the mill. Some hand piling or scattering may be needed where slash disposal equipment cannot be used. In group selection cutting, slash can be concentrated for burning in the openings.

Primary concerns on partially cut areas are protection of the residual stand at each cut, and protection of the new reproduction when the final harvest is made. The same criteria used in management with advanced reproduction applies here.

Management With Artificial Reproduction

On clearcut areas, good sites should be planted immediately after logging where (1) there is not a manageable stand of advanced reproduction, and (2) experience has shown that natural reproduction takes a long time. Areas prepared for natural reproduction that fail to restock in a reasonable period of time should be planted. On partially cut areas, planting should supplement natural reproduction

where stocking is inadequate after the final harvest. A minimum goal should be 300 well-established spruce seedlings.

Hand scalping will probably be adequate to prepare the site on most spruce plantations. In areas with a heavy cover of herbaceous vegetation or dense sod, machine methods will have to be used. Broadcast burning can be used where there is no advanced reproduction or residual stand.

Plant only stock meeting Forest Service Regional standards. Spruce planting stock requires exacting care; it should be lifted when dormant and treated as dormant plants during transport to and storage at the planting site. Plant in the spring using the hole method. New plantings should be protected from livestock and rodents.

Until reliable techniques have been developed for the central and southern Rocky Mountains, direct seeding of spruce is not recommended as an operational practice.

Multiple-Use Silviculture

In addition to being the most productive timber type in the central Rocky Mountains, spruce-fir forests are also the highest water yielding, and are valuable wildlife, recreation, and scenic areas. Because of increasing demands on limited forest lands from a rapidly expanding population, management must consider all key land uses. The kinds of stands that appear desirable for increased water yields, preservation of the forest landscape, maintenance of scenic values, and improvement of wildlife habitat have been suggested in a general way by both research and observation.

For water production, about one-third of a drainage or Working Circle should be in cleared openings five to six times tree height. These openings would be maintained by recutting the trees when they reached about one-half their original height. The remaining two-thirds of the area should be retained as continuous high forest where trees would be periodically harvested on an individual tree basis. Big-game use of spruce-fir forests is also improved by the combination of cleared openings and high forests. However, since natural succession is likely to replace the more palatable forage species that initially come in the openings, one way to integrate timber, water, and wildlife production is to periodically cut new openings about four to five times tree height while allowing older openings to regenerate.

Permanent forest cover at least in part is preferred in recreation areas, travel influence zones, and scenic view areas. With some form of partial cutting, forest cover can be retained while at the same time replacing the old with a new stand. However, the visual impact of logging must be minimized. To reduce the sudden and severe visual impact on the landscape viewer, openings cut in stands should be a repetition of natural shapes.

WHAT DO WE NEED TO KNOW

Silvicultural practices are needed that will establish and maintain stands with the form, structure, and arrangement needed to integrate all land uses. For the timber resource these include: (1) classifying spruce-fir forests into categories of similar stand characteristics as the basis for identifying management potentials in existing stands; and (2) testing silvicultural systems and cultural practices in stands of different characteristics.

Classification of vegetation in the spruce-fir zone is needed to guide the manipulation of forests for multiple use. For the timber resource this includes: (1) what species grow together and how to recognize the plant associations; (2) how these species reproduce, grow, and interact in a variety of situations; (3) the response in terms of successional trends and the stability of various plant associations to different management prescriptions; and (4) the extent to which research results can be extrapolated.

Prediction of growth and yield of spruce-fir is needed to provide the basis for decisions on (1) site quality classes that will repay the cost of thinning and other cultural treatments; (2) levels of growing stock — including frequency of thinnings and intermediate cuttings — to meet different management objectives; (3) length of rotation cutting cycles, and allowable cut for different cutting methods, management goals, and utilization standards, and (4) the place of timber management in multiple-use management. Better decisions can be made regarding key uses when the timber potential can be forecast.

Methods of obtaining natural and artificial regeneration have been fairly well developed for Engelmann spruce. What is needed now is information on (1) seed production in relation to source to work out relationships between the source and the amount and periodicity of seed productions; and (2) germination and survival under different environmental conditions to identify limiting factors and provide estimates of the probability of seedling establishment. These data, together with existing information on seed dispersal distances, will permit simulation of the regeneration phase of spruce for different environmental conditions.

THE LODGEPOLE PINE TYPE

Lodgepole pine forests cover extensive areas between 7,500 and 10,500 feet elevation in Colorado and Wyoming, but reach maximum development in the upper montane and lower subalpine zones on south and west slopes between 9,000 and 10,000 feet elevation (see fig. 1). These forests are the second largest timber resource in Colorado and Wyoming (see table 1). The imbalance in age-class distribution is not as serious as in spruce-fir forests, but many of the pole-sized timber stands are either overmature, overly dense, or growing on sites not likely to produce a tree of saw-log size (see table 2).

WHAT DO WE KNOW ABOUT LODGEPOLE PINE FORESTS

Habitat Conditions

The climate where lodgepole pine grows in the central Rocky Mountains is warmer and drier than the higher spruce-fir zone, but is still characterized by extremes. Most precipitation is received as snowfall, and precipitation is likely to be deficient for short periods during the growing season. Best development occurs where annual precipitation is more than 21 inches.

Soils where lodgepole pine grows are young, and the profile is poorly developed. Soil parent materials are varied and mixed. Glacial deposits, alluvial fan sediments, stream alluvium, and materials weathered in place predominate. Crystalline rocks such as granite, gneiss, schist, granodiorite, and rhyolite are the principal bedrocks.

Climax and Succession

Lodgepole pine is an aggressive pioneer and invader, whose occurrence is due largely to fire. Lodgepole pine is considered to be seral in stands that have either a mixed overstory composition or contain appreciable amounts of advanced reproduction of other species. Where lodgepole pine stands are the result of catastrophic fires that have burned so often and so extensively that large acreages are nearly pure pine, it is considered a subclimax because there is no seed for the normal climax species. It is also considered stable when held on an area by factors other than climatic.

Stand Conditions

Lodgepole pine occurs as an even-aged, single-storied, and sometimes overly dense forest only where favorable fire, seed, and climatic conditions once combined to produce a large number of seedlings. Elsewhere, it grows as two-aged, single- or two-storied stands; three-aged, two- or three-storied stands; and even-aged to broad-aged multi-storied stands.

Stands of pure lodgepole pine occur frequently over much of the area it occupies, especially where stands originated after repeated fires. However, mixed stands of lodgepole pine and other species are not uncommon. In mixed stands the overstory can either be pure pine or pine and the climax species, with the climax species in the understory.

Damaging Agents

Lodgepole pine forests are susceptible to windthrow after cutting. While the tendency to windthrow is usually attributed to a shallow root system, susceptibility is related to the kind and intensity of cutting, soil depth and drainage, defect, stand density, and topographic exposure (fig. 8).

The mountain pine beetle is the most serious insect pest in mature to overmature lodgepole pine stands. Usually, outbreaks reach epidemic proportions only in stands that contain at least some older trees 14 inches in diameter and larger. After the larger trees are killed, beetles attack the smaller trees until the outbreak subsides. The only practical silvicultural control in heavily infested stands where the trees are 10 inches in diameter and larger is to harvest the infested trees, burn the unmerchantable material, and regenerate a new stand. In infested stands with a good stocking of smaller diameter classes, removal of the older and larger trees effectively regulates the mountain pine beetle.

Dwarf mistletoe, the most serious disease affecting lodgepole pine, reduces growth and increases mortality. It is most damaging in stands partially opened up by cutting, mountain pine beetles, or windfall, and is of least consequence on regenerated burns. Separation of the old and new stands by clearcutting and felling unmerchantable trees is the best way to control dwarf mistletoe. Partial cutting should be avoided unless the infection is rated class 2 or less (fig. 9).

Figure 8.—Severe blowdown in a lodgepole pine stand after a heavy shelterwood cut that removed 60 percent of the basal area. Fraser Experimental Forest, Colorado.

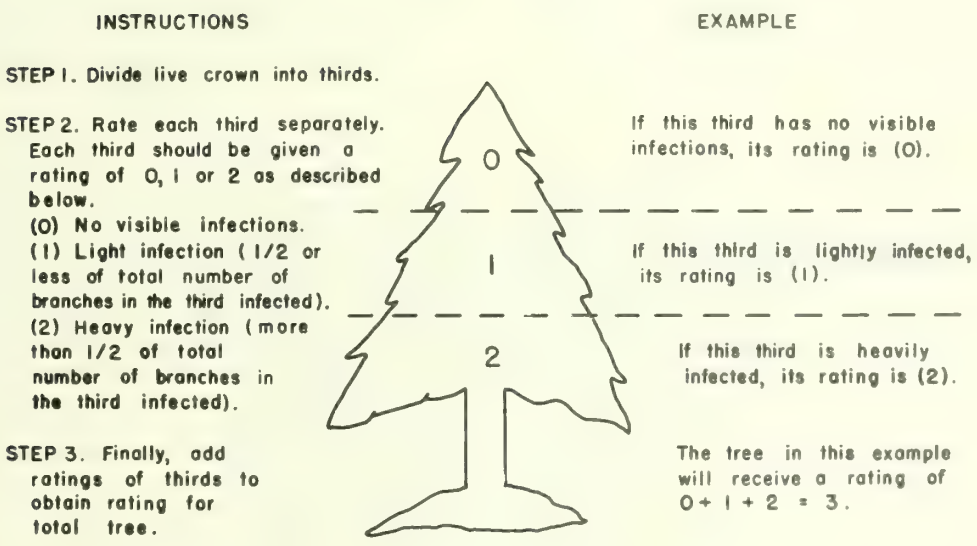
INSTRUCTIONS
EXAMPLE
STEP 1. Divide live crown into thirds.
STEP 2. Rate each third separately. Each third should be given a rating of 0, 1 or 2 as described below.
(0) No visible infections.
(1) Light infection (1/2 or less of total number of branches in the third infected).
(2) Heavy infection (more than 1/2 of total number of branches in the third infected).
STEP 3. Finally, add ratings of thirds to obtain rating for total tree.
0
1
2
If this third has no visible infections, its rating is (0).
If this third is lightly infected, its rating is (1).
If this third is heavily infected, its rating is (2).
The tree in this example will receive a rating of 0 + 1 + 2 = 3.

Figure 9.—The 6-class mistletoe rating system.

Comandra blister rust is a common canker disease in the cental Rocky Mountains, but damage has been most extensive in northern Wyoming. Sanitation salvage cutting is about the only practical way of controlling the disease in forest stands.

Natural Reproduction and Early Survival

Lodgepole pine reproduces from seed. It is a prolific seed producer with good crops borne at 1- to 3-year intervals. Throughout much of the central Rocky Mountains, lodgepole pines bear an abundance of serotinous cones that remain unopened on standing trees. However, in some areas, the cone habit is known to be largely nonserotinous. Because the variability in cone habit greatly affects regeneration, each stand must be examined before cutting to determine cone serotiny.

In stands with serotinous cones, seed released from cones attached to the slash and cones scattered on the forest floor is the most important dispersal. Maximum release from this source takes place the first year after cutting. The amount of seed stored in closed cones is usually adequate for regeneration, providing that logging slash bearing cones is carefully handled.

In stands with nonserotinous cones, seed is dispersed from standing trees, largely by the wind. The maximum size of opening that will restock in a reasonable amount of time is probably no greater than about four to five times tree height, because seedfall drops off rapidly as distance from source increases, with most seeds falling within about 200 feet.

The several sources of seed available for natural reproduction include: (1) serotinous cones in the logging slash (a one-shot opportunity), (2) nonserotinous cones on trees either standing around the perimeter of cutover areas or on the area cut, and (3) nonserotinous cones on new reproduction 5 to 10 years old. One of the significant considerations in the kind of seed source to leave in stands with nonserotinous cones is its resistance to windthrow.

Viable seeds of lodgepole pine that survive overwinter normally germinate in the early summer following snowmelt. Lodgepole pine is noted for its ability to establish on burned surfaces after wildfire, but germination and initial survival have usually been better on exposed mineral soil, and disturbed duff and mineral soil than on other seedbed types because of more stable moisture conditions. Germination and early seedling development are usually considered best in full sunlight, but on some sites radiation intensities under full exposure can create temperature and moisture conditions critical to seedling establishment, especially when precipitation during the growing season is low or irregular. For example, on clear days in early summer, exposed soil surfaces are rapidly dried out and heated to high temperatures. Few seeds can imbibe sufficient water to germinate, and many newly germinated seedlings are killed by stem girdle or drought. Shade either from light slash or a residual overstory reduces excessive heating and drying of the soil surface.

Newly germinated seedlings are especially susceptible to damage from early fall frosts, but older seedlings are seldom damaged by frosts during the growing season. The combination of warm daytime temperatures, nighttime temperatures below freezing, and saturated soils unprotected by snow cover in the early fall are conducive to frost heaving. Shade reduces mortality from frost damage by reducing loss of radiant energy from soil and seedlings. Disease, animals, and vegetative competition also limit regeneration success. Newly germinated seedlings are killed by damping-off fungi early in the growing season when seedbeds are damp. Snowmold fungi occasionally cause damage and death to both natural and planted lodgepole pine seedlings if they remain under the snow too long. Young lodgepole pine seedlings are vulnerable to trampling damage. Birds clip the seedcoats from newly germinated seedlings, and mountain voles and pocket gophers destroy established seedlings. Understory vegetation is usually a major constraint to successful seedling establishment.

Site Quality

The conventional measure of site index is the average height of dominant trees in relation to age. The height growth of lodgepole pine, however, is influenced by stand density probably more than any other North American conifer. The height-age relationship of lodgepole pine is thus a valid estimate of site index only when height growth is adjusted for any reduction due to density. Curves of the height, age, and density (measured as Crown Competition Factor, CCF) relationships of dominant lodgepole pine have been prepared that are suitable for estimating site index (fig. 10).

Conventional methods of site determination cannot be used on lands that are nonforested, or that contain trees either too young or unsuitable for site determination. Site index of lodgepole pine in north-central Colorado and

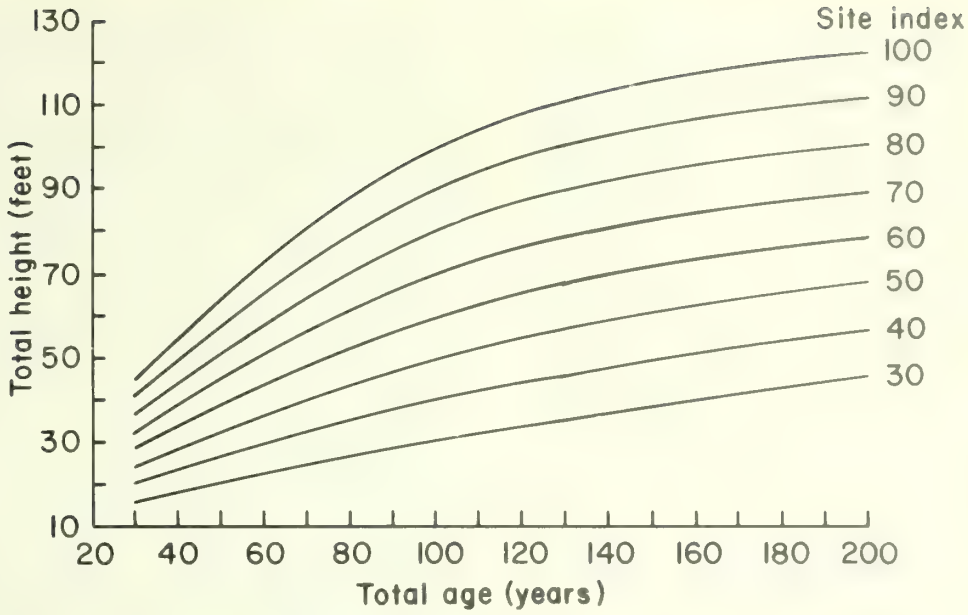

Figure 10.—Site index curves for lodgepole pine at Crown Competition Factor (CCF) levels of 125 or less. Base age: 100 years, total age.

outh-central Wyoming can be estimated from nvironmental factors, but such site indexes ave not been developed for other areas in the entral Rocky Mountains.

Growth and Yield

Lodgepole pine often reproduces so abundantly following fire or clearcutting that competition for growing space does not permit good development without artificial thinning (fig. 11). Evidence of stand density control on growth in young stands is well documented: (1) diameter growth is greatest at the lowest density and slowest at the highest; (2) height growth is reduced by high stand densities, but the response of height growth to thinning has been variable; (3) basal area increment decreases when basal area per acre exceeds about 80 ft^2 ; (4) cubic foot volume increment increases with an increase in stand density, except in stagnated stands.

Growth estimates based on Forest Survey data indicate that average annual growth over all sites in old-growth lodgepole pine is about 25 to 40 fbm per acre. This low productivity is

gure 11.—Dense 60-year-old stand of second-growth lodgepole pine. Medicine Bow National Forest, Wyoming.

largely due to the great number of small trees. As old-growth lodgepole pine sawtimber and poletimber stands are harvested, they must be managed from the regeneration period to final harvest. Furthermore, there are many stands of young growth that must be brought under management. Some of these stands have been thinned once but are in need of a second thinning.

Yield tables for managed stands are the basis for timber management planning. Field and computer procedures for preparing yield tables for managed stands of lodgepole pine, including those infected with dwarf mistletoe, realistically simulate (1) stand growth, (2) response to thinning, and (3) reproduction cutting by any of the even-aged systems.

WHAT PRACTICES CAN WE NOW RECOMMEND

Regeneration Silviculture

Harvest cutting methods applicable to old-growth lodgepole pine forests include clearcutting, and shelterwood and group selection cuts. Seed tree and individual tree selection cutting are usually not applicable in lodgepole pine stands. The choice of cutting method depends upon management goals, but stand conditions, windfall, disease and insect susceptibility, and the risk of potential fire damage — all of which may vary from place to place on any area — limit the options available for individual stands. For example, partial cutting should not be used in high wind-risk situations, in stands where mountain pine beetle infestations are building up, or where the severity of dwarf mistletoe infection exceeds class 2.

Management With Clearcutting

In pure lodgepole pine stands there is seldom a manageable stand of advanced regeneration. If regeneration is present, it usually has been suppressed for so long that it has no future management potential. In mixed stands, where the associated species are spruce and fir, there is frequently a manageable stand of advanced reproduction. Procedures developed for the management of advanced reproduction in spruce-fir stands should be followed.

Most lodgepole pine clearcut areas will be regenerated with either natural or artificial reproduction after logging. Cutting unit layout, logging plans, and slash disposal and seedbed treatment should be designed to facilitate seed dispersal, promote seedling survival and establishment, and create favorable growing conditions.

Clearcutting can be by patches, blocks, or strips. The size of opening likely to restock is influenced by the seedbed and whether the seed is dispersed from open or closed cones. Stands with serotinous cones have maximum flexibility in the size and shape of openings cut that will restock, but natural regeneration is normally a one-shot opportunity. However, there is no advantage to cutting openings larger than 30 to 40 acres even for dwarf mistletoe control and smaller openings — 10 to 20 acres — would provide a supplemental seed source in trees standing around the perimeter.

In stands with nonserotinous or intermediate cone habit, the cutting unit must either be designed so that seed from the surrounding timber margin reaches all parts of the opening, or the cut made in a good seed year after cones are mature and seed is shed. Otherwise, plan on artificial regeneration. The maximum size of opening likely to restock to natural reproduction is about four to five times tree height. On south slopes, openings should be smaller — about two to three times tree height. If larger openings are cut, the area beyond effective seeding distance must be planted.

Slash disposal and seedbed preparation will be needed after clearcutting. In stands with serotinous cones, careful handling of slash is required to avoid destruction of seed-bearing cones. If concentrations of slash are piled or windrowed for burning, the piles and windrows must be kept small and well distributed. The lighter areas of slash can be either lopped and scattered or rolled and chopped. Slash can be handled the same way in stands with nonserotinous or intermediate cone habit, except that it can be treated when green. Slash also can be broadcast burned.

Lodgepole pine sites scheduled for planting should be reforested immediately after logging and slash disposal. Areas prepared for natural reproduction that fail to restock in 3 years should be planted; otherwise additional seedbed preparation is likely to be needed. A minimum goal should be 1,200 well-established seedlings per acre where timber production is a primary objective, otherwise a minimum of 600 seedlings per acre is sufficient. Methods of handling planting stock, seedbed preparation, and planting techniques developed for Engelmann spruce also apply here.

Techniques for direct seeding have not been worked out for the central Rocky Mountains, but direct seeding on prepared seedspots has been successful elsewhere.

Management With Partial Cutting

Shelterwood cutting should be used in single-, two-, and three-storied stands, and overwood removal in multi-storied stands. Group-selection cutting is usually appropriate only in stands where natural openings occur or small openings are required to meet management objectives. Group selection is not recommended where disease and insect problems impose limitations on how stands can be handled. The overstory will usually be removed in more than one step. The amount of basal area removed at each entry and the number of entries is determined by stand characteristics, windfall risk, and insect and disease problems. Partial cutting requires careful marking of individual trees or groups of trees to be removed, and close supervision of logging.

In **mixed stands** and to a lesser extent in pure stands, the manager must determine whether he has an acceptable stand of advanced reproduction and decide if he is going to manage it before any cutting begins. Furthermore, he must reevaluate the advanced reproduction after the final harvest and slash disposal to determine the need for supplemental stocking. The same criteria used to evaluate advanced reproduction in spruce-fir stands apply here.

Preventing logging damage to the residual merchantable trees and advanced reproduction —where an acceptable stand is to be managed —at each cut, and new reproduction at the time of final harvest, is of primary concern. To minimize damage, skid roads must be laid out and marked on the ground so that they can be used to move logs out of the woods at each cut. Trees should be felled into openings as much as possible in a herringbone pattern that will permit logs to be pulled onto the skid roads with a minimum of disturbance. Furthermore, as much down dead and cull material as possible should be skidded out to minimize slash treatment.

Some treatment of logging slash and unmerchantable material will probably be needed after each cut, however. Treatment should be limited to lopping and scattering, chipping along the roadway, and hand piling and burning to minimize damage. Machine piling will damage the residual, and broadcast burning slash will not only damage the residual stand, but may destroy the seed supply in stands with serotinous cones. In nonserotinous stands or stands with intermediate cone habit to be regenerated largely by new reproduction, a partial overstory canopy or trees standing around the margins of small openings provide a seed source within effective seeding distance and an environment compatible with germination and seedling establishment. In stands with serotinous cones, the seed supply is largely in the cones attached to the slash or scattered on the ground. The manager must make sure that a suitable seedbed is provided after the seed cut with shelterwood cutting, and after each cut with group selection.

Multiple-Use Silviculture

Timber production is only one of the key uses of lodgepole pine forests in the central Rocky Mountains. They occupy areas that also are important for water yield, wildlife habitat, recreation, and scenic beauty. Forest managers must consider how these areas are to be handled to meet the increasing demands of the public. The kinds of stands that appear desirable for increased water yields, preservation of the forest landscape, maintenance of scenic values, and improvement of wildlife habitat are similar to those suggested for spruce-fir forests.

WHAT DO WE NEED TO KNOW

Current silvicultural practices need to be modified to incorporate the maintenance of scenic values and the integration of other multiple-use values. For the timber resource, methods of establishing and maintaining high forests and grouping existing lodgepole pine stands of like characteristics will provide the forest manager with the basis for such decisions as: (1) the kind of stands that can be converted directly to partial cutting systems, and those that must be started new; (2) the amount of overstory that can be maintained in stands with different characteristics; and (3) the cultural practices needed to meet specific objectives.

The classification of vegetation needed to guide the manipulation of spruce-fir forests is also needed for those areas occupied by lodgepole pine.

The field and computer simulation techniques now available for the management of even-aged stands must be expanded to include uneven-aged stands and irregular stand structures needed for multiple use.

Methods of obtaining regeneration have been largely developed for lodgepole pine stands with serotinous cones. What is needed now are natural and artificial reproduction procedures for stands with nonserotinous cones, especially on south slopes and in tension zones.

SOUTHWESTERN MIXED CONIFER FORESTS—INCLUDING ASPEN

Mixed conifer forests of the Southwest include mixed stands of commercial species in Arizona, New Mexico, and southwestern Colorado that occupy sites more moist than usually occupied by pure stands of ponderosa pine (fig. 12). The most common overstory species, more or less in order of abundance, are Douglas-fir, ponderosa pine, white fir, Engelmann spruce, aspen, southwestern white pine, blue spruce, and corkbark fir. Mixed conifer forests may occur in a variety of mixtures of the above species. At one extreme the overstory may be nearly pure ponderosa pine with other species abundant in the understory, while at the other extreme the overstory may be predominantly Engelmann spruce. Stands of Engelmann spruce and corkbark fir without other species are not considered mixed conifer forests, but where they integrate with other conifers, they are part of the mixed conifers. Aspen management in the Southwest is tied closely to mixed conifer forests.

The principal mixed conifer forest areas (fig. 13) can be found below 6,000 feet elevation in canyon bottoms and on protected north slopes in the pure ponderosa pine type, but most grow at elevations above 8,000 feet. Mixed conifers are largely replaced by spruce-fir above 10,000 feet elevation. Mixed conifer forests, which occupy about 2.5 million acres of highlands in the Southwest, are of less importance in terms of total commercial forest land and sawtimber volume than spruce-fir in southwestern Colorado or ponderosa pine in Arizona and New Mexico (see table 1). As is usually the case with relatively unexploited forests, the largest proportion of Douglas-fir and other components are in old-growth sawtimber-sized stands (see table 2). Aspen, however, is about equally divided between saw-log and pole-sized stands.

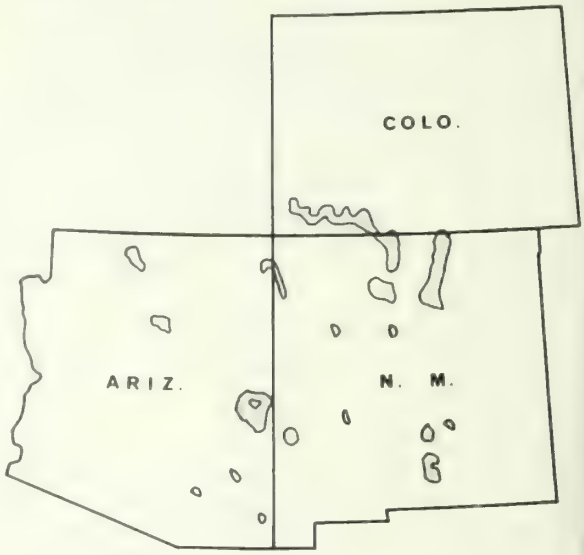

Figure 13.—Mixed conifer areas in the Southwest.

WHAT DO WE KNOW ABOUT MIXED CONIFER FORESTS

Habitat Conditions

The climate, soils, and landforms where mixed conifers grow are similar to spruce-fir

Figure 12.—A virgin mixed conifer stand in the Southwest.

forests at the higher elevations and ponderosa pine forests at lower elevations, but mixed conifer forests are wetter than ponderosa pine and warmer than spruce-fir. Snowfall is heavy, and there is considerable summer precipitation. Spring and early summer comprise the dry season, and moisture may be deficient for short periods of time. Windfall is most likely shortly after snowmelt or during severe autumn storms, when the soil is saturated. Destructive winds blow mainly from the southwest.

Climax and Succession

In mixed conifer forests, Douglas-fir and white fir are considered the predominant climax species below 8,500 feet on north slopes and 10,000 feet on south slopes. Natural forest succession — as well as it is now understood — on mixed conifer and spruce-fir sites after complete forest removal is shown in figure 14. Most mixed conifer forests seem to have followed wildfires. Initial stages are usually forbs, grass, aspen, or oak scrub. Ponderosa pine sometimes restocks these burns. If grass becomes established, coniferous invasion is usually slow. If a seed source is available, Douglas-fir and white fir invade pioneer pine stands. In the absence of a coniferous seed supply, aspen will persist for decades, but in the presence of a seed supply, aspen is quickly invaded by tolerant conifers. Oak scrub may also persist a long time.

Stand Conditions

There is considerable variability in stand conditions and characteristics in mixed conifer forests that complicates the development of silvicultural systems needed to bring these forests under management. Some stands are single-storied, others are two-, three- and multi-storied. Single-storied stands are uncommon in mixed conifer forests, but occur more frequently in spruce-fir and aspen forests. Two-storied stands are likely to be predominantly ponderosa pine or aspen in the overstory, with an understory mostly of other species. Some three-storied stands are the result of partial harvesting of single- or two-storied stands. Multi-storied stands are most common in mixed conifer forests. Multi-storied stands have usually resulted from the irregular deterioration of older age classes with time. Douglas-fir frequently predominates among older trees, but is often outnumbered by white fir in the younger age classes. In some stands, these species are largely replaced in the younger age classes by Engelmann spruce and corkbark fir.

Damaging Agents

Although variable, windfall is always a threat to trees growing in mountainous terrain. Susceptibility to windfall in mixed conifer forests is related to the kind and intensity of cutting, topographic exposure, soil depth and drainage, and such inherent species characteristics as age, size, and soundness.

Fire has frequently occurred in mixed conifer forests. These fires have often been light, killing many seedlings and saplings but generally sparing larger trees. Because mature Douglas-fir and ponderosa pine are the most resistant to fire damage, there are often more of them in many mixed conifer forests. These light fires have also contributed to the irregular structure commonly seen in virgin stands, to the presence of aspen groves, and to decay.

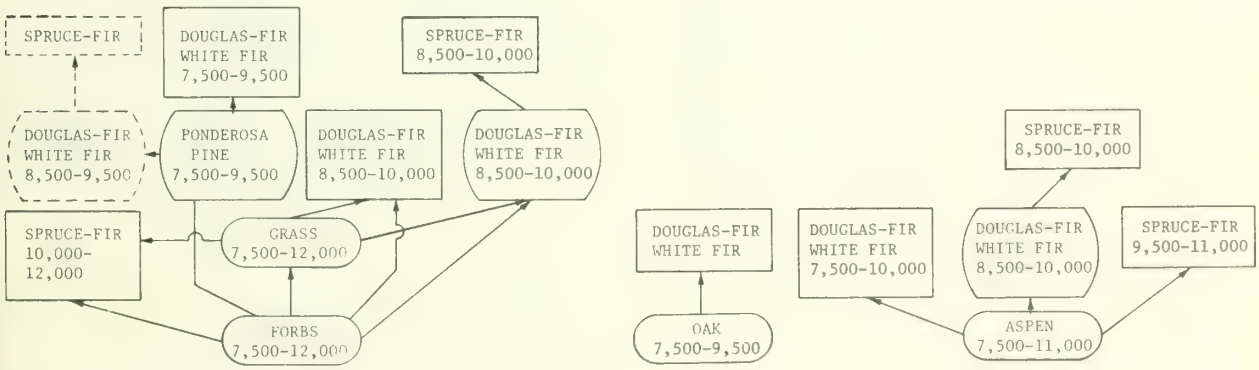

Figure 14.—Forest succession following clearcutting or severe burning of mixed conifer and spruce-fir forests in the Southwest.

Some fires have been intense, killing most trees on areas burned, but leaving a few large trees —usually Douglas-fir or ponderosa pine—as survivors. Forest succession is set back temporarily to the bare-ground stage.

The most important insect pests in mixed conifers are bark beetles and defoliators. The spruce beetle and Douglas-fir beetle attack mature to overmature trees in stands where spruce and Douglas-fir predominate. Outbreaks may develop in heavy blowdown, in trees damaged by forest fires, in concentrations of large logging slash, or in stands weakened by defoliating insects. Once outbreak levels have been reached, young vigorous trees may also be killed or damaged. Spruce beetle outbreaks are best controlled by removing poor vigor and infested trees, followed by the spraying or burning of cull material and infested trunks.

Outbreaks of western budworm periodically damage Douglas-fir and white fir. Infestations develop in young as well as overmature forests. Outbreaks result in dieback, and the dead leaders serve as centers for decay. Growth is reduced but trees commonly recover. The western tent caterpillar periodically defoliates aspen stands. Severe outbreaks may last several years and are always accompanied by a severe reduction in growth. Some stands may be essentially destroyed. In others, the outbreak may persist for several years and then collapse from natural causes.

Dwarf mistletoes reduce growth and seed production and increase mortality in southwestern mixed conifers. Infections are most important in young trees. Heavy infection of understories is less of a prospect in mixed conifer stands than in ponderosa pine stands because each mistletoe species in southwestern mixed conifers has a principal host. Douglas-fir dwarf mistletoe is the most serious, and occurs throughout the range of Douglas-fir in the Southwest. Southwestern dwarf mistletoe is found almost throughout the range of ponderosa pine. Though very damaging, it is less serious in mixed conifer stands because ponderosa pine is seldom numerous in the understory. The dwarf mistletoes on other species are not found regionwide, but they may cause severe damage where they occur.

Trunk rots are widespread in overmature trees. They cause loss of volume and predispose trees to windbreak.

Natural Reproduction and Early Survival

All mixed conifers reproduce from seed, while aspen reproduces by suckering. Blue spruce bears moderate to heavy cone crops in most years. Substantial cone crops of Douglas-fir and Engelmann spruce are frequent, while corkbark fir and white fir cone crops are more sporadic. Ponderosa pine cone crops tend to be lighter at mixed conifer elevations than lower down. The seeds of all conifers except white pine are dispersed by the wind. Seedfall into cleared openings diminishes rapidly as distance from source increased, with most seeds falling within 300 feet of the upwind timber edge (fig. 15). White pine seed is large and wingless, and dispersal beyond the immediate perimeter of the crown is mostly by rodents.

The seeds of white and corkbark firs and some white pine seeds germinate in the spring following snowmelt. The other mixed conifers germinate mainly during the summer rainy season, with ponderosa pine germination continuing into late summer. Germination and initial survival of mixed conifers are best on seedbeds with a constant supply of available

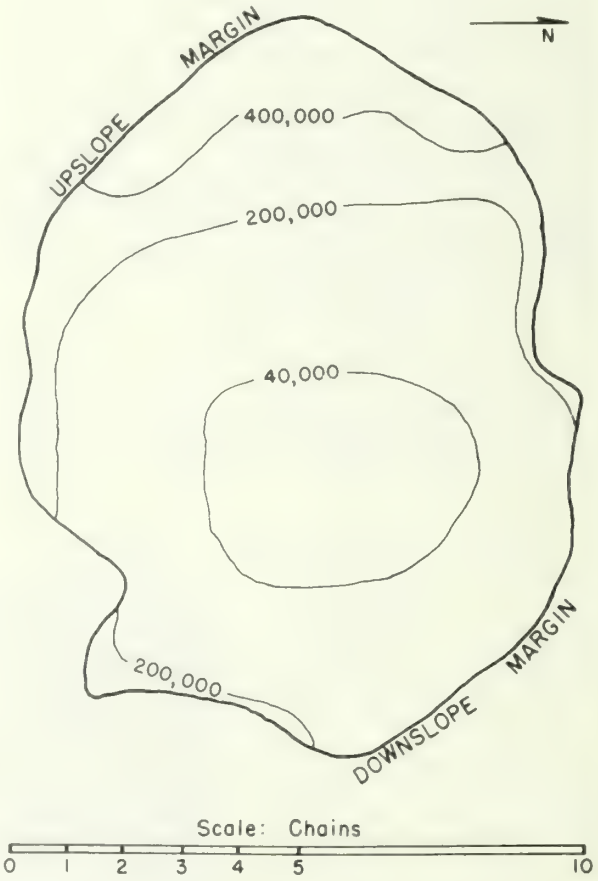

Figure 15.—Number of sound seeds dispersed into a mixed conifer clearcut during a good seed year. Apache National Forest, Arizona.

soil moisture. For example, mineral soil with a thin layer of needle litter that acts as a mulch is usually a good seedbed, whereas duff is a poor seedbed because it dries out rapidly.

Light is essential to seedling survival and growth, but Engelmann spruce, the true firs, and Douglas-fir do not establish readily in the open. Much mortality in the absence of shade is due to drying, but light injury may be a contributing factor. On the other hand, the pines, aspen, and apparently blue spruce are well adapted to establishment in the open. The initial growth of aspen is unsatisfactory in shade, and the growth of all conifers that survive the first 2 or 3 years is better in the open than in shade.

The growth of all seedlings is restricted by low nighttime temperatures early in the growing season. Severe frosts, particularly where cold air collects, may also kill new growth. Newly germinated seedlings are especially susceptible to early fall frosts, while older seedlings are more often damaged in the spring. Sequences of freezing and thawing temperatures when the soil is wet and bare of protective snow cover results in frost heaving. The shallow-rooted species — the spruces, corkbark fir, and Douglas-fir — are most susceptible. Shade prolongs snow cover and reduces the daily thawing of bare ground and the incidence of ground freezing in late spring and early fall. During the spring-early summer dry period, soil moisture deficits may develop that are critical to initial seedling survival, but usually do not kill established seedlings except on severe sites. Fall soil moisture deficits are less limiting to seedling establishment.

Biotic factors also limit mixed conifer regeneration success. Squirrels and other small mammals consume significant amounts of seed, and voles and pocket gophers kill established seedlings. Small seedlings also die from depletion of soil moisture by dense grass stands, and smothering by cured herbaceous material and aspen leaves. Sheep and big-game animals, especially deer, severely browse aspen and all species of conifer reproduction. Young seedlings are also vulnerable to trampling damage by both livestock and big-game.

Site Quality

Site index is the conventional method of estimating potential productivity in forest stands. Curves of the height-age relationship suitable for estimating site index have been prepared for Engelmann spruce (see fig. 5), southwestern ponderosa pine (fig. 16), and aspen (fig. 17), but not for other species of mixed conifers in the Southwest.

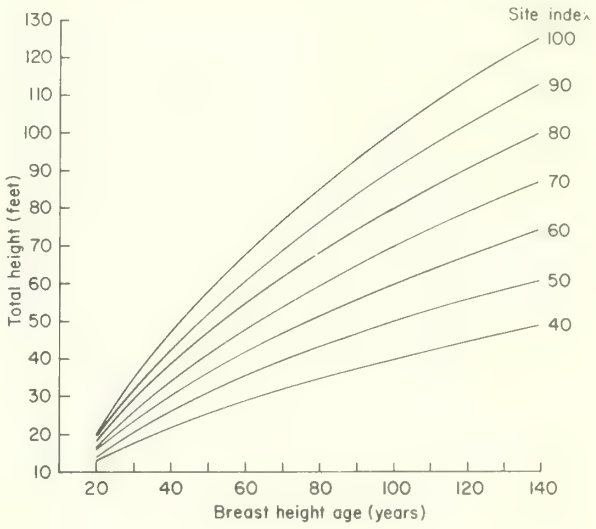

Figure 16.—Site index curves for young growth ponderosa pine in northern Arizona. Base age: 100 years, breast height.

Figure 17.—Site index curves for aspen in southern Rocky Mountains. Base age: 80 years, breast height.

Growth and Yield

A high proportion of mixed conifer forests are in mature to overmature stands. Growth estimates from inventory data indicate that growth is much below what can be expected in managed stands. As old-growth mixed conifer stands are converted to new stands, they will be managed from the reproduction period to the final harvest. The only growth prediction tool available for mixed conifer species is for southwestern ponderosa pine. Data are now being collected to develop a similar yield prediction procedure for Engelmann spruce.

WHAT PRACTICES CAN WE NOW RECOMMEND

Regeneration Silviculture

The recognized harvest cutting methods applicable to mixed conifers include clearcutting, and shelterwood and selection cutting and their modifications. The choice of cutting methods depends on management goals, but stand structure and composition, and wind, insect, and disease problems impose limitations on how stands can be handled.

Aspen Management

Aspen stands commonly occur either as single- or two-storied stands. Single-storied stands should be clearcut — preferably in fairly large acreages to reduce browsing damage — if a market exists for small round products. Unmerchantable trees should be felled and all debris and logging slash cleaned up by broadcast burning or machine piling and burning. This should be all that is necessary to regenerate the area. If there is a market only for saw logs, a three-cut shelterwood is usually appropriate because the unmerchantable portion of these stands is susceptible to windthrow and disease problems if the stands are opened up too much. It may be desirable to convert single-storied stands to conifer forests by planting the areas with shade-tolerant conifers. Provision should be made to release the conifers from aspen suckers.

Two-storied aspen stands usually have a mixed conifer or spruce-fir understory (fig. 18). If this understory is sapling size, the overstory should be removed in a single cut to release the conifers. Aspen suckers will fill in the gaps. If the understory is composed of seedlings or trees larger than sapling size, the overstory should be removed in two or three steps.

Figure 18.—An aspen overstory with a mixed conifer understory in the Southwest.

On partially cut areas and where there is a manageable understory of reproduction, protection of the residual stand during logging is of primary concern. The logging plan should include skid roads laid out and marked on the ground so that they can be used to remove logs at each cut. Trees should be felled into openings as much as possible, and at an angle that will permit logs to be pulled onto the skid roads with a minimum of disturbance. If it is necessary to fell trees at a poor angle for winching onto skid roads, logs should be bucked into short lengths. Some slash treatment will probably be needed after each cut, but it should be confined to concentrations. Where slash disposal equipment cannot operate, slash should be hand piled for burning in small piles or scattered.

Conifer Management

Mixed conifers occur in a wide variety of stand structures and species composition (fig. 19). Single-storied stands are likely to be strongly dominated by a single species. If stands are not widely infected with dwarf mistletoe they can be partially cut. Shelterwood should be used if the stands are even-aged and uniformly spaced, and group selection if they are uneven-aged, clumpy, and irregular. The amount of basal area to be removed at each entry, the number of entries, and the size of group openings depends largely on the windfall risk situation.

In some stands, even-aged, well-stocked overstories of ponderosa pine dominate an understory of mixed conifers. If the understory is seedlings and saplings, an overwood removal in one step can be used in these two-storied stands to release the conifers. If the understory is pole sized, a two- or three-step shelterwood should be used. To maintain ponderosa pine dominance, clearcutting in small patches and planting pine is recommended. Where the overstory in two-storied stands consists of species other than pine, the understory is likely to be understocked. If not badly infected with mistletoe, a shelterwood that removes the overstory in a series of partial cuts is recommended.

In three-storied stands and multi-storied virgin stands where dwarf mistletoe is not severe, the overstory can be removed in a two- or three-cut shelterwood or by group selection. Cutover multi-storied stands are sometimes poorly stocked. They can be managed as uneven-aged stands under a selection system or converted to even-aged management by cutting the older trees. Understocked openings should be planted or otherwise treated to stimulate prompt regeneration.

On all partially cut areas and those clearcut with a manageable stand of advanced reproduction, protection of the residual stand is important. The same care in logging and slash disposal recommended for aspen stands with a conifer understory apply here.

Single-storied stands badly infected with dwarf mistletoe can be regenerated by the shelterwood method if the infected residuals are removed as soon as regeneration permits. The regeneration will require one or more sanitation cuttings after the overstory has been removed. Seriously infected stands with more complex structures may also be manageable by shelterwood or selection methods because of host specificity. Other severely infected stands or parts of stands should be clearcut. Since clearcut mixed conifer areas do not regenerate well naturally, they should be planted.

Planting is also needed on nonstocked areas and to fill in gaps after partial cutting. In areas where big-game and livestock use is heavy, species like the spruces and white pine should be favored over Douglas-fir and ponderosa pine. Tolerant conifers should be planted under aspen. On exposed sites below about 9,000 feet, ponderosa pine is most likely to survive. Above 9,000

Figure 19.—A virgin multi-storied mixed conifer stand in the Southwest.

feet on exposed sites, Engelmann spruce will have to be used, but it must be provided with dead shade. Planting procedures developed for spruce-fir forests apply here.

Multiple-Use Silviculture

Silvicultural prescriptions in mixed conifer stands must consider uses other than timber production. Esthetic and recreational considerations may require the maintenance of a continuous high forest cover. On the other hand, a combination of cleared openings and high forests increases water yields, favors livestock use, and benefits certain kinds of wildlife. Openings cut in stands should be a repetition of natural shapes that will complement the landscape.

Aspen has outstanding multiple use potentials. It is highly regarded for its scenic beauty, especially where other types of vegetation cover extensive areas. Aspen stands without coniferous understories provide considerable forage for big-game and livestock. Aspen is best perpetuated by burning or clearcutting.

WHAT DO WE NEED TO KNOW

Silvicultural prescriptions and cultural practices must be developed in mixed conifer stands of differing structures and species composition that will establish and maintain high forests. Such forests can be used alone or in combination with cleared openings to meet the needs of a variety of uses including timber production. For the timber resource the needs include: (1) classifying southwestern mixed conifer habitats into ecologically similar units; (2) classifying mixed conifer stands into different stand types considering both composition and structure; (3) identifying potentials and problems of different stand types on different habitat types; and (4) testing silvicultural systems and cultural practices in stand types on different habitat types.

Beyond the classification of habitats and stands, we need to know: (1) how to recognize habitat types in areas which have been altered by past activities; (2) how the various mixed conifer species reproduce, grow, and interact in the different habitat and stand types; and (3) the physical responses and successional trends following management prescriptions.

Growth prediction tools for southwestern mixed conifers are or soon will be available for only two species — ponderosa pine and Engelmann spruce. It will be necessary to either develop (1) composite yield tables based on these two species, or (2) growth prediction tools for each mixed conifer species. In any event, volume tables and methods of estimating site index must be prepared for each species before yields can be forecast.

Methods of obtaining natural and artificial regeneration must be explored more fully. Information is needed on (1) regeneration requirements of individual species by habitat types, (2) physiological response of seedlings and planted stock to environmental factors by habitat types, (3) environmental and biotic factors limiting regeneration success for different habitat and stand types, (4) cultural practices and protective measures to modify limiting factors for different habitat and stand types, (5) methods of evaluating and managing advanced growth, and (6) what species to favor for specific management goals.

Southwestern ponderosa pine covers extensive areas in the Southwest (Arizona, New Mexico), Colorado, and Utah (fig. 20). In the Southwest, ponderosa pine grows between 5,500 and 9,500 feet elevation, but reaches maximum development at 7,000 to 8,000 feet. In Colorado, it is found between 5,000 and 9,000 feet elevation. Ponderosa pine is the largest and most valuable timber resource in Arizona and New Mexico, but is less important in Colorado (see table 1). Most of the ponderosa pine forests are in sawtimber-sized stands, but there are more poletimber stands in Colorado than in the Southwest (see table 2). Stocking in all three States is generally low.

Figure 20.—Occurrence of ponderosa pine in the Southwest.

WHAT DO WE KNOW ABOUT SOUTHWESTERN PONDEROSA PINE FORESTS

Habitat Conditions

The climate where ponderosa pine grows can be described as moisture deficient. Average annual precipitation ranges from 18 to 21 inches, but the distribution varies over the area. In the Southwest, April through June are the driest months and July through September the wettest. In Colorado, precipitation is more uniformly distributed from April through September. Considerable snow falls in most winters, but it is less important in terms of total precipitation than for forest types at higher elevations. In years of low snowfall, deep soil freezing occurs. The growing season is fairly long (average 135 days), and monthly mean temperatures vary from about 29° F in January to 68° F in July.

Soil parent materials vary according to the bedrock from which they originate. In the Southwest, soils derived from basalt occur on about half the area, while most of the remaining area has soils derived from granite, sandstone, and limestone. In Colorado, crystalline granitic, sedimentary, and volcanic rocks predominate. Soils vary widely in texture and physical and chemical properties.

Climax and Succession

Southwestern ponderosa pine occurs as a climax type between 7,000 and 8,000 feet elevation, but disturbances by fire or heavy logging have partially or completely converted many climax ponderosa pine stands to other plant communities (fig. 21). The kind of vegetation initially occupying the site usually determines the length of time it will take to return to a ponderosa pine forest. At higher and lower elevations, where ponderosa pine integrates into mixed conifer and pinyon-juniper forests, it loses its climax characteristics unless special effort is made to retain it in the stand.

Figure 21.—A clearcut ponderosa pine area which failed to regenerate because of a lack of seed source. Site is now occupied by Arizona fescue and mountain muhly grasses.

Stand Conditions

In the Southwest, ponderosa pine forests are usually open-grown, poorly stocked, and interspersed with occasional meadows and parks. These forests occur mainly as irregular, uneven-aged stands consisting of small even-aged groups, varying in size from a few trees to several acres (fig. 22). Past cutting practices involving a variety of selection methods have tended to preserve the uneven-aged structure. However, occasional stands are even-aged where fires, open areas, and early clearcuttings have regenerated.

Pure ponderosa pine stands normally occur where the species is climax. Mixed stands, however, are not uncommon. Both pure and mixed stands may have an understory of younger trees.

Figure 22.—Uneven-aged ponderosa pine stand in northern Arizona.

Damaging Agents

Wind is a primary cause of damage to mature and overmature ponderosa pine, especially when windstorms in the fall and spring are accompanied by heavy precipitation. Lightning also damages old-growth ponderosa pine, but it is not always fatal.

Damage from wildfire occurs mainly in young age classes, but hot fires will destroy all trees in the burned area. Where large trees are not killed, fire scars reduce the value of the butt log and provide entry points for wood-rotting fungi.

Dwarf mistletoe is the most widespread and damaging disease affecting southwestern ponderosa pine (fig. 23). It infects trees of all age classes, and may kill small trees in a few years. Older and larger trees die more slowly. Heavily infected stands should be clearcut and the area replanted. In low density stands with a manageable understory, dwarf mistletoe may be treated

Figure 23.—Dwarf mistletoe damage on southwestern ponderosa pine.

by an overstory removal followed by a thinning and pruning of understory trees.

Western red rot is the most important heart rot of ponderosa pine. It causes loss of volume and predisposes trees to windbreak. Sanitation-salvage cutting is the most effective silvicultural control of red rot.

The mountain pine beetle is the most aggressive insect pest of southwestern ponderosa pine. It normally attacks and kills old and weakened trees, but will attack and kill vigorous, young trees when insect populations reach epidemic proportions. The roundheaded pine beetle periodically infests ponderosa pine over many areas. Infestations develop from endemic population levels in dense stands on poor sites or where trees have been attacked by other beetles. Populations may then build up and attack trees on better sites. The western pine beetle attacks trees larger than 6 inches d.b.h. that are of poor vigor.

Animals can damage ponderosa pine other than regeneration stands. For example, porcupines deform, and debark or girdle and kill pole-sized trees and young sawtimber. Twig cutting by tree squirrels normally reduces

growth and causes forked trees, but it may be so severe that trees are killed or become susceptible to attack by bark beetles.

Natural Reproduction and Early Survival

Natural reproduction success depends on an ample seed supply and adequate moisture for germination and early survival — conditions that seldom coincide. Ponderosa pine produces good seed crops only at intervals of 3 to 4 years, with lighter crops in some of the intervening years. Seed is dispersed by the wind, but is not effectively disseminated over extensive areas.

Trees vary considerably in their ability to produce cone crops. The best seed producers are vigorous dominants, 24 to 28 inches in diameter, that are free from disease or damage and show evidence of having produced good cone crops (fig. 24).

Viable seeds that survive overwinter do not germinate in the spring because, by the time seedbeds are warm enough in late May or early June, they are too dry for seeds to imbibe sufficient water. Germination usually begins with the summer rains in July, but if the rains are too light to keep the seedbeds moist or are late in coming, germination is delayed until late summer. Late-germinating seedlings are then especially susceptible to frost heaving or fall drought.

The best seedbed is loose enough so that a light layer of mineral soil covers the seeds, and has sufficient dead needle litter to prevent excessive drying. Germination may be good in heavy litter in years of high rainfall, but seedlings do not survive because of rapid drying when the rains stop. Shade from dead material benefits germination because it conserves soil moisture, but ponderosa pine seedlings that start in dense shade do not survive long unless the shade is removed. Live shade is not detrimental to germination, but grasses, shrubs, and other small trees limit seedling establishment because of intense competition for limited soil moisture. On the other hand, although ponderosa pine seedlings are not damaged by exposure to full solar radiation, side or light overstory shade improves survival and early growth by lowering temperatures, thereby reducing water losses from both seedlings and soil.

Low temperatures normally cause only minor damage in the ponderosa pine zone, but young seedlings are susceptible to freezing injury. Newly germinating seedlings, especially those germinating late in the season, are most likely to be damaged by fall frosts. Older seedlings are most susceptible to damage by early

Figure 24.—Excellent ponderosa pine seed tree. Fort Valley Experimental Forest, Arizona.

spring frosts when tissues are still succulent. Seedlings have been winterkilled, but freezing temperatures are involved only indirectly by their effects on soil moisture. Frost heaving, however, from alternate freezing and thawing of saturated soils unprotected by snow cover, is a serious cause of ponderosa pine seedling mortality. Shade reduces mortality from frost damage by reducing the loss of radiant energy from both soil and seedlings.

Diseases, insects, and animals also limit ponderosa pine regeneration success. Newly germinated seedlings are killed by damping-off fungi. Cone and seed insects destroy seed before it is dispersed. White grubs, cutworms, and tip moths damage both new and older seedlings. Small mammals cut and cache cones, eat shed seed, and kill or injure young seedlings. Birds clip the seedcoats from newly germinated seedlings, and big-game animals and livestock browse and trample small seedlings (fig. 25).

Site Quality

Site quality indicates relative productive capacity, and determination of productivity is basic to yield prediction, optimum levels of

Figure 25.—Cattle damage to ponderosa pine. Fort Valley Experimental Forest, Arizona.

growing stock, and the intensity of management. Site index, determined by the height-age relationship, is the conventional method of estimating site quality in southwestern ponderosa pine. In Arizona, southern Colorado, and New Mexico, site index is determined from curves of the height of dominant trees at breast height age (see fig. 16). Curves of the average height of dominant trees at total age are available for estimating site index on the east slope of the Front Range in northern Colorado (fig. 26). Elsewhere in Colorado, regional curves are based on the height of dominant and codominant trees of average diameter at total age. Ponderosa pine forests in the Southwest can also be grouped into three broad site classes for land suitability planning.

Growth and Yield

The effect of stand density on the growth of southwestern ponderosa pine is well documented. For example: (1) diameter growth at all ages is inversely related to residual stand density, and diameter growth decreases rapidly if stand density is not reduced at periodic intervals; (2) basal area increment increases with an increase in basal area stocking until basal area per acre exceeds about 80 ft^2 per acre; (3) height growth is unrelated to stand density, except in very dense stands; and (4) volume growth per acre increases with an increase in basal area stocking, except at very high densities.

Natural stands of ponderosa pine in the Southwest are generally poorly stocked, and low stocking is reflected by the low volumes per acre. For example, in Arizona, ponderosa pine stands average only about 6,200 fbm per acre. Average per-acre volumes are even less in New Mexico and Colorado. Fully stocked stands on good sites are capable of yields of 25,000 to 35,000 fbm per acre.

Forest management in the Southwest is in a transition to more intensive management. As old-growth stands are converted to new stands, they must be managed from the regeneration period to final harvest. Furthermore, many young stands, some of which have been thinned once, must also be brought under management. Yield tables for managed stands are the basis for timber management planning. Field and computer procedures for preparing yield tables for managed stands of southwestern ponderosa pine, including those infected with dwarf mistletoe, realistically simulate stand growth, response to growing stock levels, and reproduction cutting by any of the even-aged systems. The Southwest phase of the Westwide Growing Stock Level study plots will provide periodic checks on the simulation procedures.

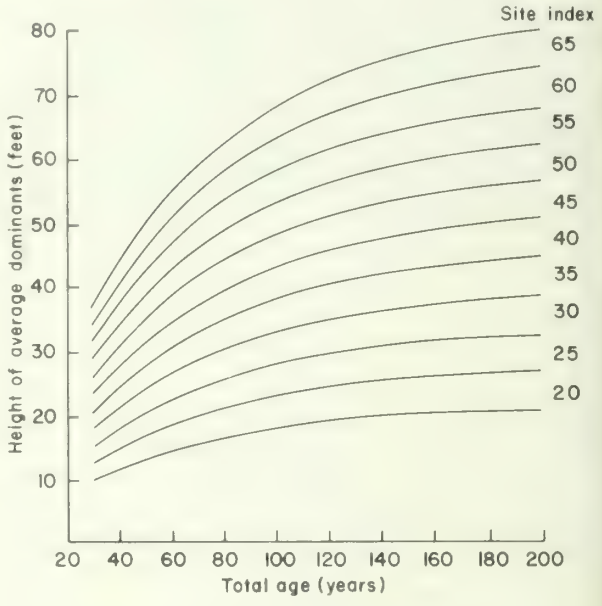

Figure 26.—Site index curves for ponderosa pine. East slope Front Range, Colorado. Base age: 100 years, total age.

WHAT PRACTICES CAN WE NOW RECOMMEND

Regeneration Silviculture

The most appropriate silvicultural systems for southwestern ponderosa pine are shelterwood and group selection cutting, but individual tree selection and clearcutting can be used under certain conditions. Many southwestern ponderosa pine stands can be managed as either even- or uneven-aged, or converted from one management system to another. The choice of cutting method depends largely on management

goals and silvicultural stand condition class, but dwarf mistletoe infection, and wind and fire risk may limit the way stands can be cut.

Even-Aged Management With Natural Reproduction

Shelterwood cutting should be used in most stand condition classes where it is desirable to manage stands as even-aged. The three-step shelterwood or a series of partial cuts is most appropriate for unmanaged stands, and a two-step shelterwood should be used for managed stands or those susceptible to windthrow. Care in logging at each cut is essential to protect the residual stand and advanced reproduction where a manageable stand exists. Precommercial thinning of sapling stands before final harvest will reduce logging damage. Other criteria developed for protection of residual stands in spruce-fir forests also apply here. If the stands are to be regenerated to new reproduction, a thorough job of site preparation is needed to eliminate competition and possible loss of the site to grass and brush. The final harvest should be made promptly after seedlings are established to release new reproduction, but protection of the reproduction from logging damage is of primary concern.

Some slash disposal will probably be needed after each cut, but it should be limited to treatment of concentrations and that needed to reduce environmental impacts. Slash should be lopped and scattered where possible. If it must be burned, piles should be kept small and scattered.

Shelterwood cutting also can be used to convert irregular, uneven-aged stands to an even-aged structure. Where there is not a manageable stand of advanced reproduction or the overstory has a heavy volume, a two-step shelterwood should be used. If the overstory is light, with a heavy understory of advanced growth, an overwood removal is appropriate.

Areas heavily infected with dwarf mistletoe should be clearcut in patches or blocks no larger than about 20 acres. If local experience indicates that these areas are not likely to restock naturally, they should be planted.

Uneven-Aged Management With Natural Reproduction

Selection cutting is appropriate in the irregular, uneven-aged stands that occur over much of the Southwest where it is desirable to maintain the uneven-aged structure. Trees may be cut as individuals scattered over the area or in groups, but group selection is the preferred method where the stand condition class and management goals permit its use (fig. 27). Under group selection, the naturally occurring groups, which average from about 1/2 to 2 acres in size, are treated according to their needs. For example, old decadent groups should be cut and the area promptly regenerated by natural or artificial seeding or planting. Immature and mature groups should be given a sanitation cut to improve vigor and growing conditions. Ponderosa pine forests overstocked in the smaller and larger diameter classes, and understocked in the intermediate classes, can be converted to group selection by heavy cutting in the overstocked diameter classes. Slash should be disposed after selection cutting by lopping and scattering or burning in small piles.

Figure 27.—Group selection cutting in southwestern ponderosa pine. Trees at the right are in the group being cut. Young trees in the background came in after an earlier group selection cut.

Management With Artificial Regeneration

One of the objectives of the silvicultural systems described above is to obtain natural reproduction. Areas which do not restock or need supplemental stocking must be either planted or direct seeded.

Complete site preparation to conserve soil moisture is a must if planting or seeding is to succeed. Mechanical scarification that removes or reduces vegetative competition and prepares a good seedbed is preferred to other methods.

Planting is the most effective way to artificially regenerate ponderosa pine. Plant only stock from local seed sources that meets Forest Service Regional standards. Ponderosa pine planting stock must be carefully handled. It

should be lifted when dormant and treated as live dormant plant material during transport to and storage at the planting site. Planting may be done by hand using the hole method or by machines. The most favorable sites should be planted first, taking advantage of dead shade. Success is better with spring than fall planting. A minimum goal is 680 trees per acre.

Direct seeding is more economical and flexible than planting, but it is less reliable. Freshly burned and logged areas are the most promising sites for direct seeding. Spot seeding is the most effective method; it requires the least seed and the seed can be placed in the best locations. Broadcast seeding is faster and more flexible, but less effective and requires more seed. The best time to seed is during the last part of June so that the seed is exposed to damaging agents for a shorter period of time before the summer rains begin. Only local seed sources should be used.

Successful seeding or planting is only the first step in reforestation. New plantations must receive care and be protected from damage or loss from fire, insects, rodents, vegetative competition, and browsing and trampling animals.

Intermediate Stand Management

Intermediate cuts are (1) thinnings, and (2) release, improvement, and salvage cuttings. These are made from the time a stand is established until the time to establish the replacement stand. These cuts cover the major portion of the rotation period, and are normally made at periodic intervals to increase growth and quality, and to salvage material that would otherwise be lost.

Multiple-Use Silviculture

Timber management activities in southwestern ponderosa pine have a great impact on all forest uses for wood, forage, recreation, water, and wildlife. Standard silvicultural systems and practices will provide multiple use benefits and sustained yield with only minor adjustments in some instances. For example, by maintaining less basal area and overstory density, and using a longer cutting interval than is optimum for timber production under shelterwood cutting, both the amount and quality of forage can be increased for both wildlife and livestock. Forage production can also be increased by group selection cutting.

In travel and water influence zones, recreation sites, and scenic view areas, individual tree selection cutting can be used to improve natural beauty. Cutting should be light and the number of trees removed varied throughout the stand to develop stands in these special use areas that will contain trees from seedlings to yellow pines.

WHAT DO WE NEED TO KNOW

Silvicultural practices developed for timber production in southwestern ponderosa pine must be modified to establish and maintain stands with the form, structure, and arrangement needed to integrate all key land uses. For the timber resource, these modifications include: (1) grouping pine forests into ecological land units of similar stand characteristics as a basis for identifying management potentials for existing stands, and (2) testing cutting and other cultural practices to attain management goals in stands of different characteristics.

Classification of vegetation in the southwestern ponderosa pine zone is needed as a basis for improved forest descriptions and preparation of management prescriptions needed to guide the manipulation of forests for multiple use. For the timber resource this includes: (1) what ecological land units are present and how to recognize them in areas that have been altered by past activities; (2) how ponderosa pines reproduce, grow, and interact with abiotic and biotic agents in a variety of situations; and (3) how stands respond in terms of succession and the stability of various habitat types to different management prescriptions.

Field and computer simulation procedures developed for the prediction of growth and yield of even-aged ponderosa pine in the Southwest must be expanded to include uneven-aged stands and those with irregular stand structures that can be used for timber production and other key land uses. For both even- and uneven-aged management, the biotic potential and response criteria must be identified for different habitat types to aid the manager in making sound decisions for multiple use management.

Methods of obtaining artificial regeneration have been largely developed for southwestern ponderosa pine, but prompt and adequate natural reproduction has not been attained after cutting in many areas. Natural reproduction requirements are known, but the factors limiting regeneration success and the methods needed to reduce losses must be identified for different habitat types. The most critical needs, however, are to determine the stand densities and cultural practices under shelterwood cutting in different stand condition classes, and the size of opening cut under group selection cutting, required to obtain natural regeneration.

BLACK HILLS PONDEROSA PINE FORESTS

Ponderosa pine forests cover about 1 million acres in the Black Hills of South Dakota and Wyoming, and the Bear Lodge Mountains of Wyoming (fig. 28). These forests form a unique, isolated segment of the interior ponderosa pine type, but management is simplified in the Black Hills because these forests reproduce readily and prolifically, and are free of dwarf mistletoe. Ponderosa pine is the principal timber resource, and it usually occurs in pure stands (see table 1). The original forests have been largely converted to second growth, and the distribution of age classes is better than for central and southern Rocky Mountain timber species. However, the largest proportion of the area still supports the remnants of old-growth sawtimber stands, mostly with regeneration below, and the smallest proportion is in seedling and sapling stands without overstory (see table 2).

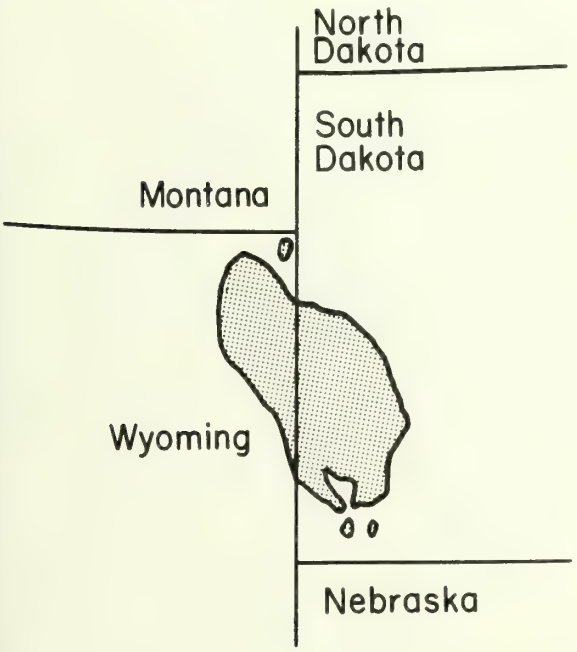

Figure 28.—Occurrence of ponderosa pine in the Black Hills and Bear Lodge Mountains.

WHAT DO WE KNOW ABOUT BLACK HILLS PONDEROSA PINE FORESTS

Habitat Conditions

The climate of the Black Hills is characterized by an orographic rain belt where precipitation is increased and temperatures reduced from the surrounding plains by the mountains themselves. Average annual precipitation varies from 17 inches in the south to 28 inches in the north, 60 percent or more of which falls as rain from April to September. January and February are usually the driest months, and May and June the wettest. The growing season averages about 100 days, and monthly mean temperatures vary from 22° F in December to 68° F in July.

The Black Hills and Bear Lodge Mountains have four visible and distinctive gross geomorphologic features: (1) a "hogback ridge" of mesozoic sedimentary rocks encircling the area, (2) a "red valley" of less resistant sedimentary rock, (3) a limestone plateau, and (4) a central core of crystalline rock (fig. 29). The main timber-producing areas are the crystalline core area, which is characterized by rough to rounded hills and divides generally ranging from 4,300 to 6,000 feet elevation, and the limestone plateau. In the east the plateau forms a narrow ridge that occasionally flattens out to narrow uplands with elevations of 3,600 to 4,400 feet; in the west it forms wide, rather level divides separated by narrow, steep valleys that range in elevation from 4,500 to 7,000 feet.

Soils in the Black Hills have not been surveyed, but their general profile characteristics approximate a loam to silty clay loam of the Grey Wooded Soils Group.

Climax and Succession

Ponderosa pine occurs as a climax type that essentially dominates most forest areas in the Black Hills. A variety of other native tree species are only minor components. For example, white spruce frequently grows in pure stands along streams, lower slopes, and upper north-facing slopes in the northern Hills, but it occupies only about 2 percent of the total commercial forest land. Occasionally ponderosa pine is temporarily replaced by other plant communities after fire or other disturbance, but it usually reoccupies most sites rapidly.

Stand Conditions

In the Black Hills, transitional two-aged stands composed of a light overstory of residual old-growth trees above dense second growth occur on more acres than any other stand condition. Dense, uniform, even-aged stands free of overstory and mostly immature occupy most of

LEGEND
Tertiary igneous intrusive rocks
Tertiary sedimentary rocks
Mesozoic rocks from Newcastle Sandstone (Lower Cretaceous) to top of Upper Cretaceous
Mesozoic rocks below Newcastle Sandstone (Lower Cretaceous). Includes Spearfish Formation, which is mainly Triassic but partly Permian
Paleozoic rocks
Precambrian granite
Precambrian metamorphic rocks
25 miles
Red valley
Hogback ridge
Rapid City
Central crystalline area
Limestone area

Figure 29.—Geomorphologic features of the Black Hills.

the remaining forest area. Uneven-aged stands can be found occasionally where pine has invaded grassy upland parks or old burns, and there has been prolonged protection from wildfires. Ponderosa pine stands are typically pure in the Black Hills.

Damaging Agents

Ponderosa pine trees that grow in dense stands have diameters too small for their heights, poorly developed root systems, and asymmetrical crowns. Abrupt reduction in stand density by a single thinning usually results in death or deformity from bending, breaking, or uprooting caused by wind and snow.

In much of the Black Hills, wildfires can burn any month, but midsummer through fall is the maximum hazard period. Mature stands of well-spaced trees are less susceptible to damage from crown fires than dense stands, but hot fires will destroy all trees on an area. Large trees that survive ground fires may be scarred so that the value is reduced and the trunks are susceptible to decay.

The most aggressive and damaging insect pest of Black Hills ponderosa pine is the mountain pine beetle. It normally attacks and kills older trees and those weakened by overstocking, but will attack and kill vigorous younger trees when insect populations reach epidemic proportions. Periodic epidemics that require direct control are likely to diminish in the Black Hills as overstocked stands are converted to thrifty stands. The red turpentine beetle is also found in the Black Hills, but it is usually a secondary cause of mortality, attacking trees weakened by other factors.

Western red rot and associated decay fungi cause large volume losses in old-growth timber. The impact of these diseases is reduced in young, thrifty, managed stands.

Of all animals that damage ponderosa pine beyond the seedling stage, porcupines are the most serious and persistent threat to tree growth and yield. The most desirable trees are usually attacked, and debarking and stem girdling will either kill or deform the affected trees.

Natural Reproduction and Early Survival

Ponderosa pine in the Black Hills is a dependable seed producer. Good to excellent crops, by local standards, normally occur about every 2 to 5 years, with light crops or complete failures in the intervening years. Seed is disseminated by the wind; effective dispersal distance from ponderosa pine trees is only about three to four times the crown radius, however. The combination of ample seed and favorable spring and summer precipitation usually makes natural reproduction abundantly available—a unique characteristic in ponderosa pine forests.

Viable seeds that survive overwinter normally germinate in the spring when seedbeds are moist and warm enough for seedlings to emerge. The best seedbeds are mineral soil, or a combination of mineral soil and unincorporated organic matter which is loose enough so that a light layer of soil covers the seeds. With a constant supply of moisture available during the growing season, however, Black Hills ponderosa pine will germinate and become established on a wide variety of seedbeds.

Germination and early seedling development are usually considered best in full sunlight, but light shade from overstory trees or slash is also beneficial to early seedling survival. The limited competition that favors the development of pine seedlings also favors the development of competitive vegetation, however, and the site may be lost to grass, forbs, or shrubs unless regeneration is promptly established. Ponderosa pines that start in deep shade do not survive or develop unless the shade is removed.

Drought infrequently limits regeneration success in the Black Hills, and low temperatures normally are not a problem, although newly germinated seedlings are susceptible to freezing injury from fall frost.

Diseases, insects, and animals also influence regeneration success. Damping-off fungi kill newly germinated seedlings, especially where seedbeds are kept damp. Mice and voles eat shed seed, and voles, rabbits, and porcupines kill or injure young seedlings. Big-game animals and livestock browse and trample small seedlings.

Site Quality

Evaluation of site quality is the key to focusing effort where timber production has the greatest potential. Site index is the best method of determining site quality in the Black Hills. Curves of the height-age relationship have been prepared that are suitable for Black Hills ponderosa pine stands where the age of index trees is at least 70 years old, and past crowding has not materially restricted height growth (fig. 30).

Very often in the Black Hills, the conventional method of site index cannot be used because either there are no trees present or they are unsuitable for measurement. Site index for either the crystalline or limestone areas can be estimated from equations based on soil and topographic parameters.

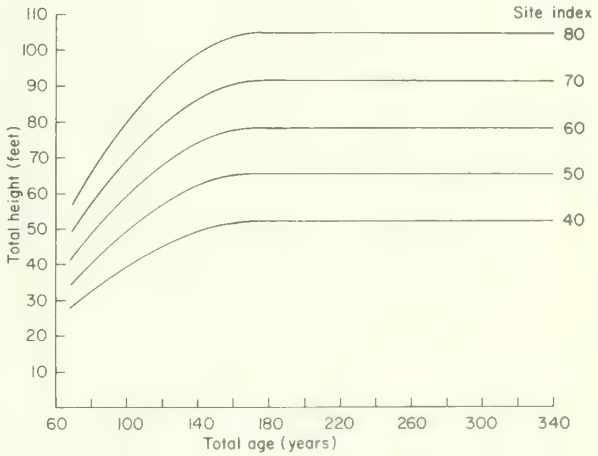

Figure 30.—Site index curves for ponderosa pine in the Black Hills. Base age: 100 years, total age.

Growth and Yield

Extremely high stand densities — often more than one tree per square foot — are common to naturally regenerated stands of Black Hills ponderosa pine (fig. 31). Since these dense stands do not thin themselves well naturally, artificial thinning is needed to reduce competition for growing space. Thinning effectively reduces mortality, stimulates diameter growth in proportion to the reduction in stand density, increases height growth, alters stem form, and concentrates increment on the best growing stock. Basal area increment in thinned stands increases as basal area per acre increases to about 80 ft^2 per acre, although the rate of increase tends to gradually diminish with each successive addition of growing stock. Cubic volume increment increases in a similar manner.

The operable and unreserved original old-growth ponderosa pine stands in the Black Hills have been largely converted to well-stocked and manageable second-growth. In addition, there are many stands of young growth that originated after fires or early cutting, some of which have been thinned at least once, others are overstocked. All of these stands need to be brought under more intensive management for a variety of uses. Yield tables for managed stands are the basis for timber management planning. Field and computer procedures for preparing yield tables for Black Hills ponderosa pine produce simulations of (1) stand growth, (2) response to thinning, and (3) reproduction cutting by any of the even-aged systems. The manager can use the computer simulation program to produce a series of yield tables for different combinations of site quality, growing stock levels, cutting cycles, and rotation ages that will show projected outcomes in response to different cultural treatments, and select the one that best meets his management goals. The Black Hill Westwide Growing Stock Level study plots provide periodic checks on simulation procedures.

Figure 31.—Stagnated stand of Black Hills ponderosa pine saplings, 63 years old with 5,800 stems per acre.

WHAT PRACTICES CAN WE NOW RECOMMEND

Regeneration Silviculture

Regeneration silviculture in the Black Hills has been learned by experience during nearly a century of harvesting that has included all silvicultural systems, and led to the replacement of the original old-growth by well-stocked, manageable second-growth stands. The most obvious lesson from this varied experience is that any regeneration system can be applied to Black Hills ponderosa pine, but even-aged management is the most compatible with the strong natural tendencies of the species, silvicultural condition classes, and regulation of cut for timber production, and best meets other management objectives.

Even-Aged Management With Natural Reproduction

The shelterwood system is the best harvesting method for most ponderosa pine condition classes in the Black Hills because it takes advantage of the species' natural habit of forming even-aged stands. Furthermore, shelterwood cutting combines the advantages of continuous vegetative protection of the site, assurance of an adequate, well-distributed seed source, fair control over development of competitive ground cover, and good control over logging residue. A uniform two-cut shelterwood is the most effective and desirable, but a three-cut shelterwood may be used in very heavily stocked, mature stands where residue buildup, risk of windfall, and logging damage to reproduction pose unusual problems.

Site preparation will be needed on areas to be regenerated to new reproduction if the original stand was open enough to permit a stand of grasses, forbs, or shrubs to establish in sufficient numbers to take over the site before the new reproduction can get started. Along roads or in other high-use areas, slash should be piled and burned or chipped after each cut to reduce fire hazard and create an esthetically acceptable appearance. Elsewhere the slash can be lopped and scattered. The overwood should be removed promptly and carefully after reproduction is established to release new reproduction with a minimum of damage (fig. 32).

Figure 32.—Established 10-year-old Black Hills ponderosa pine reproduction under a shelterwood ready for the overwood removal.

Other even-aged methods have been successfully used to harvest and regenerate ponderosa pine stands in the Black Hills, and they have some advantages and disadvantages relative to shelterwood. For example, the advantages of leaving a few widely spaced trees in seed-tree cutting include less competition to the development of the new stand, less damage to new reproduction during final harvest, and less likelihood of excessive reproduction because of limited seed production potential. On the other hand, the heavy first cut leaves more logging residue that must be treated, the risk of loss of seed trees is high, and the limited overstory competition favors the development of other vegetation as well as tree seedlings.

Clearcutting is the least desirable even-aged system in the Black Hills, especially on areas without advanced reproduction. If stands are to be clearcut and regenerated naturally, either the cut should be made during or shortly after a good seedfall, or the cutover area should be no wider than about 200 to 250 feet to permit adequate seed dispersal from the surrounding uncut stand. Clearcut units can be blocks, patches, or strips with irregular boundaries for improved appearance. Clearcutting entails little risk of loss of seed source and allows the replacement stand to develop free of overhead shade and logging damage, but it generates the maximum amount of logging residue and affords little control over competitive ground cover.

Management With Artificial Regeneration

Planting or direct seeding of pine stands is largely confined to areas recently devastated by fires, tornadoes, or other catastrophies, with site indexesof 50 or more. Experience has shown that whenever a ground cover of grass, forbs, or shrubs has become established on potential planting or seeding sites, mechanical scarification to prepare a seedbed and reduce competition is essential.

Planting has been more successful than seeding in the Black Hills. Stock should be grown from seed collected as near the planting site as possible. In years of favorable moisture, 2-0 root-pruned stock provides the best combination of ease of planting, economy, and performance. Planting stock must be treated as a dormant plant from the time of lifting to the time of planting in the spring. Many sites can be satisfactorily planted by machines; those too rough or steep for machines will have to be planted by hand using the hole method. A minimum goal should be about 540 trees per acre.

Direct seeding, if it is successful, is cheaper than planting, but it is less reliable. A system that places one seed per unit distance in a furrow or one seed per prepared spot is most satisfactory because climatic factors favor the germination and survival of all seeds, while natural competition does not "thin out" multiseed spots. Seeds should be covered lightly with soil.

New plantations, originating from either seeding or planting, must be protected from damage from domestic and wild animals until trees reach sapling size.

Individual Tree Selection

The selection system as a regeneration method is out of place in the naturally even-aged forests of the Black Hills — at least in regulated stands managed for timber production — but individual tree selection can be used for other purposes. For example, individual tree selection is appropriate for improvement cuts in mature stands to maintain the health and appearance and capture the volume and value of a few high-risk trees when these stands cannot be harvested on schedule.

Selection cutting can be used as a multiple-use silvicultural system in stands where it is desirable to maintain scenic beauty, preserve the forested appearance in recreation areas, and improve wildlife habitat.

WHAT DO WE NEED TO KNOW

Ponderosa pine in the Black Hills has been under management for timber production a longer time than other Rocky Mountain timber type, and at a more intensive level. Consequently, considerable knowledge has been accumulated on the timber resource. For example, cutting practices have been developed for timber production that are sufficiently flexible that they can be readily adapted to provide the kinds of stands needed for a wide variety of uses; yield prediction tools including stand growth and response to thinning are available for managed stands under any of the even-aged regeneration systems; and both natural and artificial regeneration practices have been developed that insure success. Furthermore, current knowledge will provide much of the information necessary to predict the response of the timber resource to a wide variety of treatments, needed as input to multi-resource prediction models.

Refinements needed in silvicultural techniques to determine such things as what over-

story densities under shelterwood cutting will result in the desired amount of natural reproduction, can be handled by administrative studies. These should be made in cooperation with research at the planning stage. However, as management is intensified and silvicultural techniques improved, they must be tested by research. The Black Hills are an ideal outdoor laboratory for a wide variety of "on-the-ground" pilot studies.

The intensive use of forests in the Black Hills requires that timber management research become an integral part of multifunctional research directed toward: (1) identifying the response of plant communities to a wide variety of integrated and interacting uses, and (2) developing procedures that will provide an array of management alternatives needed to satisfy the objectives of different uses and users of Black Hills forest land.

TIMBER RESOURCE PRIORITY PROBLEMS

The summaries of existing knowledge for each forest type have described systems of management currently available, and identified where additional information is needed to develop adequate management systems for each type. Solutions to the problems listed below will require: (1) development of quantitative and descriptive models to provide a better basis for making land management decisions currently with information available, and (2) additional research and the development of procedures to fill deficiencies in existing knowledge.

Problem	Priority	Forest Type
1. Silvicultural prescriptions and cultural practices in stands of different structures, composition, and other characteristics that will establish and maintain the kinds of stands needed for a variety of uses including timber production. Descriptive models are now available for most forest types, but the suitability of available quantitative information for current resource and prediction response simulation models must be determined before deficiencies in knowledge can be fully identified.	1	Mixed conifers, spruce-fir
	2	Southwestern ponderosa pine, lodgepole pine
	3	Black Hills ponderosa pine
2. Classification of vegetation into units of like biological potential with wide applicability as a basis for understanding the ecology of the forest types, and determining the response of plant associations to different cultural treatments. Procedures for developing vegetation classifications have been standardized, and descriptive models are available for portions of most forest types. The suitability of existing quantitative information for use in current prediction models, and the identification of deficiencies in response data, cannot be determined until the classification of all forest lands is completed.	1	All forest types except Black Hills ponderosa pine
3. Prediction of growth and yield is the basis for management decisions including the place of timber production in multiple-use management. Computer simulation procedures are available to develop yield tables for managed stands from quantitative data. Single-resource response models	1	Spruce-fir, mixed conifers
	3	All pine types

for yield prediction have been developed for the pine types that must be refined for stand structures other than even-aged. The quantitative data for yield prediction in the other types is not available from existing information. Single-resource response models will provide the growth and yield data needed as part of the timber input into multi-resource response models.

4. Methods of obtaining natural and artificial regeneration. Prompt and adequate regeneration can be obtained in some types, while in others the factors limiting regeneration success have not been identified. Descriptive models of various degrees of refinement, however, are available from existing knowledge for most forest types. Current resource response and prediction models for the regeneration phase are also available, but either the quantitative data for Rocky Mountain timber types are not available from existing information, or the suitability of existing quantitative data for these models has not been determined so that deficiencies in present knowledge can be identified. Single-resource response models will provide the regeneration input into multi-resource models.

1	Mixed conifers, spruce-fir
2	Lodgepole pine, southwestern ponderosa pine
3	Black Hills ponderosa pine

Alexander, Robert R.
1974. Silviculture of central and southern Rocky Mountain forests: A summary of the status of our knowledge by timber types. USDA For. Serv. Res. Pap. RM-120, 36 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Summarizes a series of comprehensive reports on the silviculture of lodgepole pine, ponderosa pine, mixed conifer, and spruce-fir timber types. Includes what is known, what can be recommended, and what additional information is needed for each timber type.

Oxford: 614. **Keywords:** Silviculture; forest regeneration; growth-yield; *Abies lasiocarpa, A. lasiocarpa* var. *arizonica, A. concolor; Picea engelmannii, P. pungens; Pinus contorta, P. ponderosa, P. strobiformis; Populus tremuloides.*

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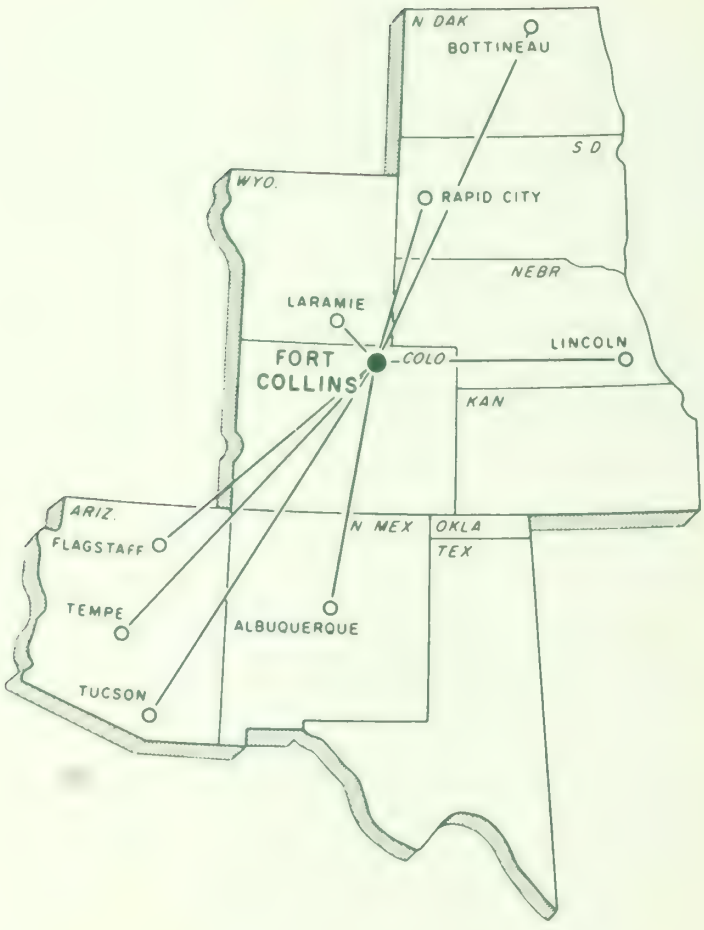
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SILVICULTURE OF SUBALPINE FORESTS IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS: The Status of Our Knowledge

by Robert R. Alexander

ABSTRACT

The status of our knowledge about the silviculture of subalpine forests in Wyoming, Colorado, and New Mexico is described. The ecology and resource of the Rocky Mountain subalpine are briefly described, followed by in-depth reviews of the spruce-fir type and lodgepole pine type. The relevant literature is included, along with unpublished research, observations, and experience. Research needs are considered as well as what is already known.

Oxford: 181\$174:187. **Keywords:** Timber management, silviculture systems, subalpine ecology, *Picea engelmannii, Abies lasiocarpa, Pinus contorta.*

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DA Forest Service
search Paper RM-121

May 1974

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by

Robert R. Alexander, Principal Silviculturist

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained in cooperation with Colorado State University at Fort Collins.*

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

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SILVICULTURE OF SUBALPINE FORESTS IN THE CENTRAL AND SOUTHERN ROCKY MOUNTAINS: The Status of Our Knowledge

Robert R. Alexander

Timber management research in the subalpine forests of the central and southern Rocky Mountains has provided a large body of knowledge on the silvics, silviculture, and management of forest tree species during the past 50 or more years. Research results and observations have been presented as individual articles in a variety of publications. Furthermore, a few summary writeups for individual species have been published for specific areas of research. Included are (1) silvical characteristics (Alexander 1958a, 1958b; Strothmann and Zasada 1957; Tackle 1961a; U.S. Department of Agriculture [USDA] 1965), (2) regeneration requirements (Roe et al. 1970), (3) planting procedures (Ronco 1972), (4) partial cutting practices (Alexander 1972, 1973), and (5) general bibliographies (Christensen and Hunt 1965, Ronco 1961a, Tackle and Crossley 1953). In Canada, summary publications on regeneration, silvics, silviculture, and management have been prepared by Armit (1966), Dobbs (1972), and Smithers (1961).

Much of the existing knowledge is still not being used by land managers, however, because it is either not readily available or not in a form and language that can be easily understood. It is the purpose of this document, therefore, to assemble in one place a comprehensive summary of available knowledge on timber management applicable to Rocky Mountain subalpine forests. Included are (1) past research done in the central and southern Rocky Mountains, (2) work done elsewhere, but corroborated by observations in the central and southern Rockies, and (3) research done elsewhere, where similar information is lacking for subalpine forests. From these facts, ideas, and observations, guidelines are developed to answer the question "to what extent are we now able to recommend timber management practices to meet a variety of uses." The report is intended specifically as a field guide for professional foresters and land managers who are responsible for prescribing and supervising the application of silvicultural treatments in the woods.

In the following sections, the report will cover (1) the ecology and resource of the subalpine, and (2) the silvics, silviculture, and management of (a) the Engelmann spruce (*Picea engelmannii* Parry)- subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) type, and (b) the lodgepole pine (*Pinus contorta* Dougl.) type. The spruce-fir and lodgepole pine types have been handled in detail separately. There is some repetition of information common to both types, but each type was handled separately to facilitate the use of available information and recommended practices by foresters and land managers. Major emphasis is placed on the silviculture and management of old-growth, and the establishment of new stands.

Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) and quaking aspen (*Populus tremuloides* Michx.) also occur in the subalpine, but their ecology, silviculture, and management are described in another report on the mixed conifers of the Southwest.

THE ROCKY MOUNTAIN SUBALPINE

ECOLOGY

The subalpine is here defined as the highest forested area in the States of Wyoming, Colorado, and northern New Mexico (fig. 1). It may occur as low as 7,000 ft elevation in northern Wyoming to as high as 12,000 ft in northern New Mexico. These subalpine forests occupy what most ecologists call the subalpine zone (9,000 ft to timberline) and the upper montane zone (7,500 to 9,000 ft).

Habitat Conditions

CLIMATE

The continental climate of the central and southern Rocky Mountains is influenced by three principal air masses: (1) Storms move into the Rocky Mountains from the Pacific Ocean during winter and early spring, carrying relatively large amounts of moisture which are released on the western slopes as the air masses rise over the mountains (Johnson and Cline

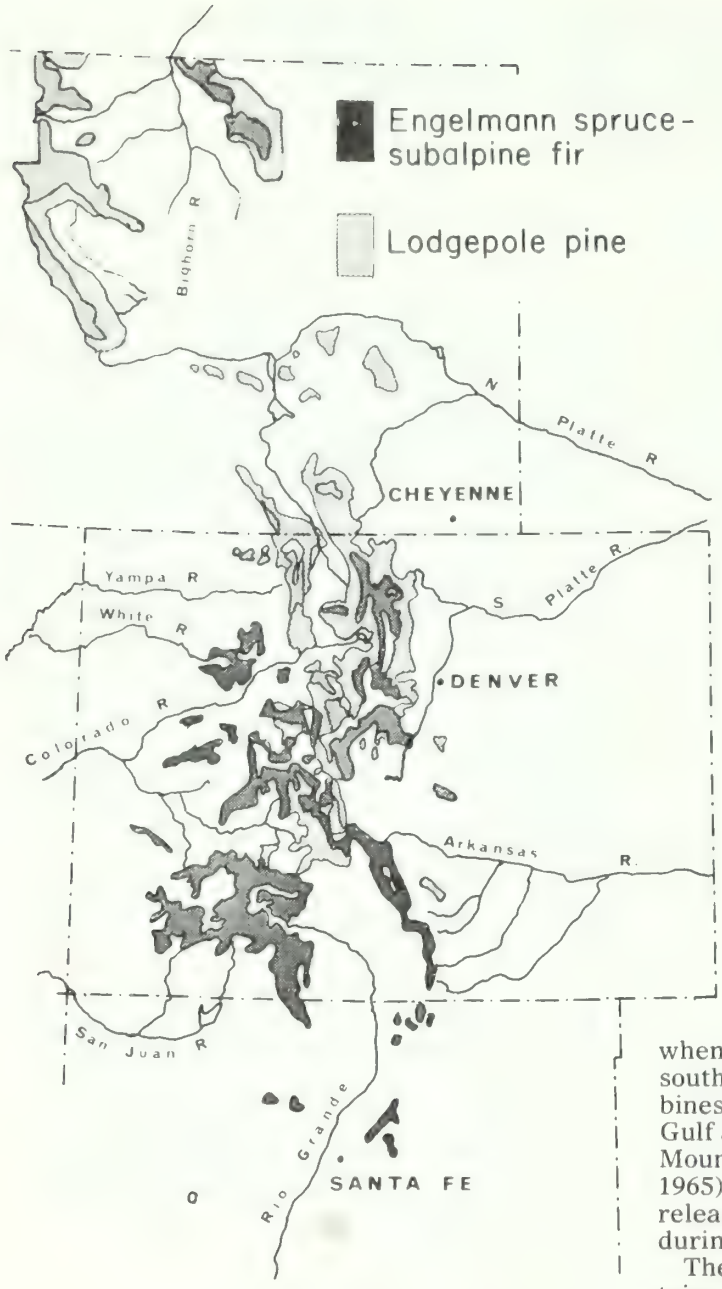

Figure 1.—Distribution of spruce-fir and lodgepole pine in the central and southern Rocky Mountains.

1965, Marr 1961, USDA 1941). Only small amounts of moisture fall on the east slopes. These same storm fronts from the west pass too far north during the summer to provide much moisture. (2) Snowfall also occurs when polar continental air moves south parallel to and east of the Front Range during the winter and interrupts the normal westerly flow (Marr 1961). (3) Normally, the warm, moist air from the Gulf of Mexico moving upslope provides moisture along the east slope of the Rockies during the spring and early summer, but at elevations below the subalpine zone (Marr 1961). However, when the storm track from the west moves south through northern New Mexico and combines with or causes a northward flow of the Gulf air, the higher southern and eastern Rocky Mountains receive moisture (Johnson and Cline 1965). In addition, convective thunderstorms release some moisture in the high mountains during the summers.

The diverse topography in the Rocky Mountains results in various microclimates in the subalpine that change significantly over short distances. In general, temperature decreases and precipitation increases with an increase in elevation (Daubenmire 1943). Climatic records for subalpine areas are mostly from valley stations, but a few representative records for forested areas are provided by Baker (1944), Bates (1924), Haeffner (1971), and Marr et al. (1968).

The climate of the subalpine can be classified as cool and humid, with long, cold winters and short, cool summers (Alexander 1958a, Marr 1961, Thornthwaite 1948, Wilm and Dunford

948). Mean annual temperature is below 35° F, nd frost can occur any month of the year. Preipitation is usually greater than 24 inches anually. Most precipitation is received as snowall, although the San Juan Mountains of southvestern Colorado and the mountains of northrn New Mexico receive considerable summer ainfall. Winds are predominantly from the vest, and may be highly destructive (Alexander 954, 1964; Alexander and Buell 1955; Daubenhire 1943).

GEOLOGY AND RELIEF

With the exceptions noted below, the Rocky Mountains are anticlinal structures with igneus and metamorphic cores (Eardley 1962, Thornbury 1965).

The Absaroka Mountain Range in northwestrn Wyoming extends in a north-south direction bout 80 miles with an average width of 50 miles. t is not a linear uplift, but a broad plateau of olcanic breccia and basalt that has been deeply roded leaving isolated, rugged mountain eaks. Glacial erosion has strongly etched the teep walls surrounding the mountain peaks Eardley 1962, Fenneman 1931).

The Bighorn Mountains of north central Vyoming are an isolated spur of the Rocky Mountains. They are characterized by a central ore of Precambrian granites and schists partly overed on the north and south by arched formations of sedimentary conglomerates that orm elevated plateaus. Steeply inclined edimentary strata flank the core on the east nd west (Bowman 1911, Fenneman 1931).

The Wind River Mountains of western Wyoning are characterized by a central core of Preambrian crystalline rock. The subsummit upands consist of granites. Older sedimentary ocks flank the mountains on the northeast side s high as 9,000 to 10,000 ft. Further to the east re foothills of sedimentary rock (Eardley 1962, Fenneman 1931).

The Front Range of the Rocky Mountains exends in a north-south direction from the Arkanas River in Colorado through the Medicine Bow Mountains in southern Wyoming (Thornbury 965). It is characterized by a central core of Precambrian granites, schists, gneisses, and dolomites that may be largely concealed in ome areas by glacial drift (Curtis 1960, Mears 953, Oosting and Reed 1952, Thornbury 1965). Sedimentary rocks are locally present, but are ot very important (Retzer 1962).

The plateaus of western Colorado consist of edimentary strata that have been pushed upward without folding over a central core of Preambrian granites. The granite rocks are exposed where rivers have dissected the sedimentary rock. Masses of igneous rock — basalt, andesite, and rhyolite — protrude through the sedimentary mantle in places to interrupt the plateau feature of this area (Bowman 1911, Eardley 1962, Fenneman 1931).

The San Juan Mountains of southwestern Colorado are distinct from other mountain ranges in Colorado because they are predominantly volcanic lavas and tuffs over sedimentary rock (Cross and Larson 1935, Larson and Cross 1956). These mountains were carved by both glacial and water erosion from the volcanic mantle whose original surface had little relief (Fenneman 1931, Mather 1957). Precambrian granites are locally abundant (Stevens and Ratte 1964). The Jemez Mountains of north central New Mexico are an extension of the San Juan Mountains.

The Sangre de Cristo Range in southern Colorado and northern New Mexico resembles the Front Range. These mountains consist of a steep north-south anticlinal uplift of intrusive Precambrian granites flanked by sedimentary shales, sandstones, limestones, and conglomerates to the east and west that occasionally overreach the crest (Eardley 1962, Fenneman 1931).

SOILS AND LANDFORMS

There is only limited knowledge of the soils and landforms of the subalpine. Soils are young, and both soils and landforms complex. General descriptions and typical soil profile characteristics are given by Johnson and Cline (1965) and Retzer (1956, 1962), but the basic information on soils and landforms needed to determine the capability and suitability of forest land for different management activities is not available.

In the lower subalpine below 9,500 ft elevation, and in the upper montane, soil parent materials are varied and mixed. Glacial deposits, alluvial fan sediments, stream alluvium, and materials weathered in place from country rock predominate. Minor deposits of aeolian sediments occur locally. Crystalline rocks such as granite, gneiss, schist, granodiorite, and rhyolite are the principal bedrocks. Of the great soils groups of major importance, Grey Wooded soils are the most extensive and occur on all aspects. Brunizems are most frequently found under mixed grasslands and open timber on south slopes. Chestnut soils occur largely on south slopes at lower elevations. Brown Forest soils are found under open timber, on stream terraces, or alluvial fans, on all except north slopes. Humic Gley soils occur extensively in poorly drained upper ends of stream valleys in

association with Bog soils. Lithosols are found whenever bedrock occurs near the surface (Johnson and Cline 1965).

In the upper subalpine above 9,500 ft, soil parent materials also vary according to the character of the bedrock from which they originated. Crystalline granitic rocks predominate, but conglomerates, shales, sandstones, basalts, and andesites commonly occur throughout the region. Most valleys have been glaciated, and glacial deposits are common. Of the great soils groups, Brown Podzolic and Classic Podzol soils occur extensively on all aspects. Groundwater Podzols are found in the more poorly drained areas. Grey Wooded soils are found where timber stands are less dense and parent materials finer textured. Brown Forest soils occur mostly at the lower margins of the upper subalpine, along stream terraces, and valley sideslopes. Lithosols, Bog, and Humic Gley soils occur under the same conditions as in the lower subalpine (Johnson and Cline 1965).

Vegetation

The diversity of habitats in the central and southern Rocky Mountain subalpine forests has long been recognized by foresters and ecologists, but the basic biological and ecological information needed to understand the vegetation associations that make up these forests, their requirements, and responses to management practices is limited. The early work of Rydberg (1915, 1916) provides a general and historical background as well as some information on specific geographical areas, and Bates (1924) discussed the general relationships of forest types.

LIFE ZONES

Altitudinal-vegetation zones have been a common way of differentiating vegetation (Daubenmire 1943, 1946, 1969; Marr 1961). In addition, there is a geographical zonation of tree species in the Rocky Mountain subalpine.

In the mountains of northern Wyoming, subalpine forests grow at elevations between 7,000 and 10,500 ft. Lodgepole pine is the principal species, but there are extensive stands of Engelmann spruce and subalpine fir above 9,500 ft. Common associates are aspen at all elevations, and Rocky Mountain Douglas-fir below 8,000 ft. Minor species include limber pine (*Pinus flexilis* James) and whitebark pine (*Pinus albicaulis* Engelm.)

In the mountains of southern Wyoming and north and central Colorado, subalpine forests are found between 8,000 and 11,500 ft elevation. Engelmann spruce and subalpine fir are the principal species above 9,000 ft on north-facing slopes and above 10,000 ft on all other slopes (Dix et al.[2], Langenheim 1962, Marr 1961). Lodgepole pine covers extensive areas between 8,000 and 10,500 ft, but reaches maximum development on south- and west-facing slopes between 9,000 and 10,000 ft elevation (Dix et al.[2]). At lower elevations, it occurs in the Douglas-fir type (Daubenmire 1943). The characteristic zonal pattern of lodgepole pine is attributed primarily to moisture at lower elevations and temperature at higher elevations (Tackle 1965). Aspen also occupies extensive areas between 7,500 to 10,500 ft (Langenheim 1962, Marr 1961). Aspen occurs in nearly pure stands on all aspects between 8,000 and 9,000 ft, and on south slopes to 10,500 ft (Dix et al.[2]). Above 9,000 ft on north slopes it usually occurs as islands of trees in grassland and shrubland (Langenheim 1962, Morgan 1969). Douglas-fir below 8,500 ft and limber pine and bristlecone pine (*Pinus aristata* Engel.) at higher elevations are minor components of these subalpine forests.

On the higher plateaus of western Colorado the altitudinal range of subalpine forests is restricted by topography to between 9,000 and 10,500 ft. Spruce and fir are the principal species, and aspen the most common associate below 10,000 ft. Douglas-fir is the most important "minor" species, but limited areas of lodgepole pine do occur.

In southwestern Colorado and northern New Mexico, subalpine forests grow from 8,500 to 12,000 ft elevation. Spruce, subalpine fir, and corkbark fir (*Abies lasiocarpa* var. *arizonica* (Merriam) Lemm.) are the characteristic species above 8,500 ft on north slopes and 10,000 ft on south slopes. Douglas-fir grows between 8,500 and 9,500 ft, but does not form pure stands. In the Douglas-fir type, aspen and white fir (*Abies concolor* (Gord. and Glend.) Lindl.) are common associates and blue spruce (*Picea pungens* Engel.) and southwestern white pine (*Pinus strobiformis* Engel.) minor associates.

Throughout the Rocky Mountain subalpine the upper limits grade into alpine tundra through an ecotone of Krummholz (Daubenmire 1943, Marr 1961, Patten 1963). Engelmann spruce is the dominant Krummholz species (Wardle 1968).

[2]*Dix, Ralph L., Ordel A. Steen, and Steven Whipple. 1972. A progress report on approaches to a classification scheme of subalpine forests of the southern Rocky Mountains. (Unpublished report by the Colo. State Univ. Dep. Bot. and Plant Pathol.; copy on file with study FS-RM-1201.27, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

SUCCESSIONAL STATUS

In classifying mountain vegetation into elevational zones, most ecologists have considered the Engelmann spruce-subalpine fir community the climax vegetation above 9,000 ft, and Douglas-fir climax in the upper montane. The monoclimax theory proposes that all other communities in the subalpine will eventually converge into these two climaxes, which are limited only by regional climate (Clements 1936). Vegetation, however, is a function of topographic, physiographic, edaphic, and biotic factors as well as climate. Not only spruce-fir and Douglas-fir, but lodgepole pine and aspen seem to form stable communities in various habitats in the subalpine (Daubenmire 1943, Langenheim 1962, Mason 1915a, Moir 1969).

Although climax forests are not easily displaced by other vegetation, fire, logging, and insects have played an important part in the successional status and composition of spruce-fir forests. Complete removal of a spruce-fir stand by fire or logging results in such drastic environmental changes that spruce and fir are usually replaced by lodgepole pine, aspen, or shrub and grass communities (Roe et al. 1970, Stahelin 1943). The kind of vegetation initially occupying the site usually determines the length of time it takes to return to a spruce-fir forest. It may vary from as few as 50 years if the site is initially occupied by lodgepole pine or aspen to as many as 300 years if grass is the replacement community (fig. 2). However, the factors that determine the kind of replacement community are not fully understood (Bates 1917b, Marr 1961, Stahelin 1943). On the other hand, attacks by spruce beetles (*Dendroctonus rufipennis* (Kirby)) have usually resulted in a change in the dominant element in the stand from spruce to fir. Because of its larger size and longer life, spruce eventually regains its dominant position in the stand, only to be removed again by spruce beetles.[3]

Most foresters and ecologists agree that lodgepole pine is an aggressive pioneer and invader, and its occurrence is largely due to fire (Clements 1910, Stahelin 1943). There is less agreement on its successional status. Foresters consider lodgepole pine to be seral in stands that are only a temporary occupant of the site. In those situations, stands have either a mixed overstory composition or contain appreciable amounts of advanced reproduction of other species such as spruce, fir, or Douglas-fir. If mountain pine beetles (*Dendroctonus ponderosae* Hopk.) attack those stands, the larger lodgepole pines are removed, thereby shortening the time required for climax species to occupy the site. On the other hand, many lodgepole pine stands are the result of catastrophic fires, and some areas have burned so often and so extensively that large acreages are nearly pure

[3]*Schmid, J. M., and T. E. Hinds. Regrowth of spruce-fir stands following spruce beetle outbreaks. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

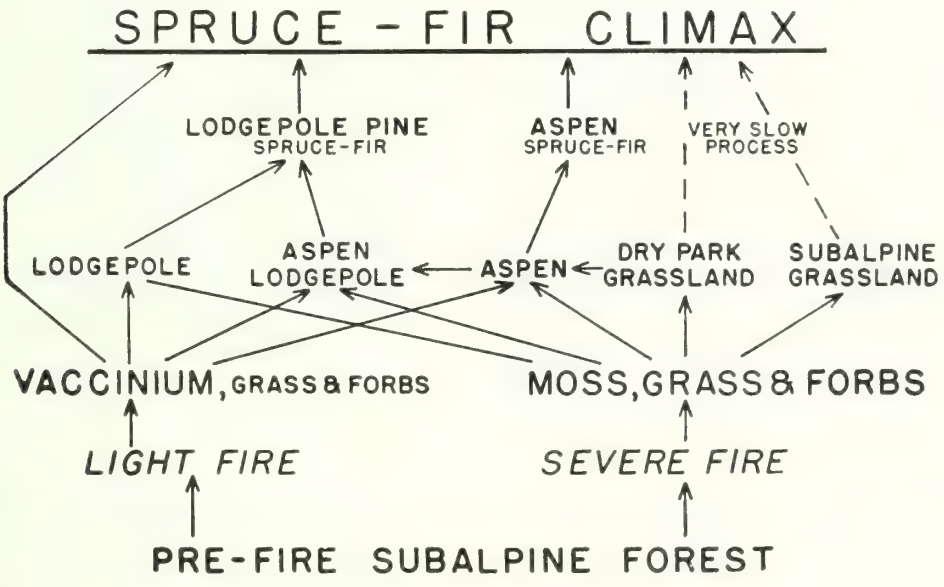

Figure 2.—Succession in subalpine forest after fire (Stahelin 1943).

pine. In those situations, lodgepole pine is maintained on the area as a subclimax because there is no seed for the normal climax species (Tackle 1961a, 1965). In other situations where lodgepole pine is held on an area by either natural or artificial means, it is also considered stable. One example of a naturally stable lodgepole community is along the east slopes of the Front Range at lower elevations. Douglas-fir, the climax species, does not reproduce itself in stands dominated by lodgepole pine because the sites are too dry (Moir 1969).

Aspen is also a pioneer species that becomes readily established by means of vigorous root suckers after disturbance (Baker 1925, Gifford 1966). It is generally considered a fire subclimax, successional to spruce and fir at higher elevations (Stahelin 1943) and Douglas-fir at lower elevations, although lodgepole pine may be an intermediate occupant of the site. However, Baker (1925) considered aspen a climax relative to management in its area of optimum development in western and southwestern Colorado. In other areas, aspen appears stable where there is either no conifer seed or the site is too dry for these species to become established.

Fire, insects, and logging have converted Douglas-fir stands to lodgepole pine, aspen, and grass and shrub communities in many places in the upper montane.

HABITAT TYPES

It is obvious that forest vegetation in the subalpine is not a simple mosaic that can be readily classified by vegetation zones. Rather it consists of a wide variety of integrated, disturbance-induced forest communities, many representing various stages of secondary succession that are difficult to treat except as developmental series related to either specific climaxes or stable plant communities. Daubenmire and Daubenmire (1968) define these relatively stable plant communities as habitat types, primarily on the basis of the relative reproductive success of trees because this indicates which species will become self-perpetuating dominants in the overstory. Habitat types are considered the basic ecological subdivisions of landscapes. Each has a distinctive potential as to successional stage, and is recognized by a distinctive overstory-understory combination (Daubenmire and Daubenmire 1968).

In northern Idaho and eastern Washington, Daubenmire and Daubenmire (1968) identified 21 habitat types, each with a distinct ecology. Subalpine fir occurs in 8 habitat types, usually as a major climax species, while spruce and lodgepole pine occur in 12, where they are considered to be successional to whatever species are climax in the particular habitat type. In western Montana, Pfister et al. (1972) using the same procedures, identified 30 habitat types. Subalpine fir occurs in 14, usually as a major climax species, while spruce and lodgepole pine occur mostly as seral species in 15 and 19 habitat types, respectively. Furthermore, management implications are keyed to each habitat type.

In the subalpine forests of Utah, Pfister (1972) identified four habitat types. Subalpine fir occurs in three as a major climax species. Spruce is a major climax species in the one habitat type where fir is missing, and a minor climax species in two others. Lodgepole pine occurs in two habitat types as a seral species. Regeneration systems are keyed to habitat types.

There have been few attempts to classify subalpine forest vegetation into habitat types in the central and southern Rocky Mountains; our knowledge of vegetation associations is fragmentary. Oosting and Reed (1952) recognized one habitat type, *Picea engelmannii-Vaccinium scoparium*, in the Medicine Bow Mountains of southern Wyoming, but their study was confined to a small area. Dye and Moir,[4] described the forest vegetation in spruce-fir forests near Sierra Blanca peak in southern New Mexico, but their observations were limited to a single habitat type, *Abies lasiocarpa-Ribes* spp./*Senecio sanguiosorboides*. Moir (1969, 1972) working in lodgepole pine forests that he considered to be climax along the east slope of the Front Range, identified two habitat types, *Pinus contorta-Vaccinium myrtillus* above 9,500 ft and *Pinus contorta-Geranium fremontii* on the drier slopes of the upper montane. Reed (1969) developed a classification using Daubenmire's procedures for the Wind River Mountains of northwestern Wyoming that recognized the following five habitat types:

1. *Pinus albicaulis-Potentilla diversifolia.* A topographic climax on upper elevation, exposed sites.
2. *Picea engelmannii-Vaccinium scoparium.* All upper slopes.
3. *Abies lasiocarpa-Pyrola secunda.* All slopes, mid-elevation.

[4]*Dye, A. J., and W. H. Moir. 1972. Spruce-fir forests at its southern distribution in the Rocky Mountains, New Mexico. (Unpublished report by the Colo. State Univ. Dep. Range Sci.; copy on file in project 1201, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

4. *Pseudotsuga menziesii* (var. *glauca*) - *Symphoricarpos oreophilis*. Lower north- and east-facing slopes.
5. *Populus tremuloides-Symphoricarpos oreophilis*. Lower south- and west-facing slopes.

Almedia (1970) in a study of lodgepole pine understory vegetation in Wyoming, identified the following plant communities:

1. *Pinus-Vaccinium*.
2. *Pinus-Carex*.
3. *Pinus-Calamagrostis*.
4. *Pinus-Elymus*.

He described the floristic composition, changes in vegetation associated with grazing and succession, and the management implications in terms of forage yields and carrying capacity for each plant community.

Steen and Dix[5] worked on a phytosociological classification of subalpine forests in the Medicine Bow Mountains of Wyoming, along the Front Range, and in the San Juan Mountains of Colorado. They tentatively identified the following vegetation associations:

1. *Picea engelmannii-Vaccinium* spp. All slopes.
2. *Picea engelmannii-Polemonium delicatum*. Upper slopes.
3. *Picea engelmannii-Cardimine cordifolia/Mertensia ciliata*. Moist lower slopes.
4. *Pinus contorta-Pachistima myrsinites*. Dry mid to lower slopes.
5. *Abies lasiocarpa-Carex geyeri/Pachistima myrsinites*. Drier midslopes.
6. *Abies lasiocarpa-Moss* spp. Dry midslopes.
7. *Populus tremuloides-Symphoricarpos* spp. Dry lower slopes.
8. *Populus tremuloides-Thalictrum fendleri*. Mid south-facing slopes.
9. *Populus tremuloides-Festuca thurberi*. Drier upper south-facing slopes.

Wirsing,[6] working on a classification of the Medicine Bow Mountains of southern Wyoming and using Daubenmire's procedures, has tentatively identified the following habitat types:

1. *Populus tremuloides-Carex geyeri*. Lower to middle south slopes.
2. *Picea engelmannii/Abies lasiocarpa-Vaccinium scoparium*. Mid to upper slopes.
   a. *Sibbaldia/Bistorta* phase (weakly defined).
   b. *Pinus contorta-Vaccinium scoparium*. (community or seral type).
3. *Picea engelmannii/Abies lasiocarpa-Carex geyeri*. Midslopes.
   a. *Pinus contorta-Carex geyeri*. (community or seral type).
4. *Pinus flexilis-Hesperochloa kingii*. Topographic climax within *Picea/Abies* habitat type.
   a. *Koeleria cristata* phase. Upper southwest-facing slopes and ridgetops.
   b. *Pulsatilla ludoviciana* phase. Drier, upper southwest-facing slopes and ridgetops.
5. *Pinus ponderosa-Carex geyeri*. Lower slopes.
   a. *Sedum lanceolatum* phase. Drier lower slopes.
   b. *Lupinus argenteus* phase. Well-drained lower slopes.

Habitat conditions in the central and southern Rocky mountains are much more diverse. The wise management of this resource will require a common system of classifying all forest lands into units of like biological potential as a means of (1) recognizing plant associations, (2) determining what species grow together, how they reproduce, and grow, and (3) anticipating their response in terms of successional trends and stability when subjected to different management prescriptions. Furthermore, the vegetation classification should be integrated with soils and landforms to provide capability and suitability classes for a variety of uses.

THE RESOURCE

Area and Volume

The subalpine forests are the largest and most valuable timber resource in Colorado and Wyoming. They are less important in terms of total commercial forest land and sawtimber volume in New Mexico.

In Wyoming, lodgepole pine grows on about half of the commercial forest land in the subalpine (table 1). Engelmann spruce and subalpine fir are second in importance in land area, followed by Rocky Mountain Douglas-fir and aspen. However, spruce-fir forests contain the largest volume of sawtimber in Wyoming. Lodgepole pine is second, followed by Douglas-fir and aspen (Choate 1963).

[5] *Steen, Ordel A., and Ralph L. Dix. 1972. A preliminary classification of subalpine forests in the southern Rocky Mountains. (Unpublished report by the Colo. State Univ. Dep. Bot. and Plant Pathol.; copy on file with study FS-RM-1201.27, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

[6] *Wirsing, John M. 1973. Forest vegetation in southwestern Wyoming. M.S. thesis, 170 p. Wash. State Univ., Pullman.*

In Colorado, spruce-fir forests occupy only about one-third of the commercial forest land, but contain nearly 70 percent of the sawtimber volume in the subalpine (table 1). Aspen accounts for more of the commercial forest land than either lodgepole pine or Douglas-fir, but less sawtimber volume (Miller and Choate 1964).

In New Mexico, Rocky Mountain Douglas-fir grows on about half of the commercial forest land in the subalpine, but it seldom grows in pure stands (table 1). Spruce and true firs occupy the second largest area of commercial subalpine forests, followed by aspen. About 10 percent of the sawtimber volume is in aspen; the remaining 90 percent is about equally divided between spruce and the true firs, and Douglas-fir (Choate 1966).

One of the features of the spruce-fir and Douglas-fir forests throughout the Rocky Mountain subalpine is the imbalance in age-class distribution (table 2). The largest proportion of area is in sawtimber-sized stands, and the smallest in seedling and sapling stands. The imbalance in age-class distribution is not as serious in lodgepole pine and aspen forests, but many of the pole-sized timber stands are either overmature or growing on sites that are not likely to produce a sawtimber-sized tree.

The acreage, volume, and stocking class data in tables 1 and 2 are only approximate. They are based on Forest Survey estimates made more than 10 years ago, and a recent study (Wikstrom and Hutchison 1971) indicates that too much area was included in the timber growing base because of inadequate information on land availability, growth capacity, and land capability. Furthermore, some of the area available and suitable for timber growing is either technologically or economically unusable at the present time (Wikstrom and Hutchison 1971).

Properties and Uses of Wood

Engelmann spruce is one of the lightest of the important commercial woods in the United States. The wood is generally straight grained, has moderately small shrinkage, can be readily air dried, and is a uniform color (McSwain et al. 1970). It is rated low in beam and post strength and in shock resistance (USDA 1955). The wood is soft and machines well for ordinary uses. It has good nail-holding properties, glues well, and is easy to work, but paint-holding properties are only average. If sufficient time is allowed, the lumber can be kiln dried without difficulty. The heartwood and sapwood are not durable when used under conditions favorable to decay. Spruce is considered somewhat resistant to preservative treatment; however, crossties have been successfully pressure treated for many years (Anderson 1956). Subalpine fir wood is light in weight, low in bending and compressive strength, moderately limber, soft, and low in resistance to shock. Shrinkage of wood is rated small to moderately large (USDA 1955).

The lumber of spruce is likely to contain many small knots. Consequently, it yields only minor amounts of select grades of lumber, but a relatively high proportion in the common grades (Mueller and Barger 1963). In the past, spruce was used principally for mine timbers, railroad ties, and poles. Today much of the lumber of both spruce and fir is used in home construction where high strength is not required, and for

Table 1.--Acreage and volume (International 1/4-inch log scale) of sawtimber on commercial forests in the central and southern Rocky Mountains, by species and States

Species	Colorado		Wyoming		New Mexico		Arizona		South Dakota	
	M acres	*MM bm*	*M acres*	*MM bm*	*M acres*	*MM bm*	*M acres*	*MM bm*	*M acres*	*MM bm*
Engelmann spruce and true firs	3,393	33,260	847	9,541	525	5,257	110	2,147	0	0
Ponderosa pine	2,347	3,783	992	2,072	4,334	16,188	3,658	22,883	1,330	3,268
Douglas-fir	1,451	5,411	701	3,566	1,000	5,025	130	1,476	0	0
Lodgepole pine	2,068	6,024	1,802	5,798	0	0	0	0	--	--
White pines	139	472	166	1,256	43	640	--	186	--	--
White spruce	0	0	--	13	0	0	0	0	23	201
Aspen	2,794	3,482	320	159	367	1,233	79	259	0	0
Total	12,275	52,731	4,853	22,632	6,269	28,343	3,977	26,951	1,534	3,716

Table 2.--Percentage of commercial forest land area in the central and southern Rocky Mountains, by species, stocking classes, and States

Species and stocking class	Colorado	Wyoming	New Mexico	Arizona	South Dakota
Engelmann spruce and true firs:					
Sawtimber	81	82	85	100	0
Poletimber	14	14	5	--	0
Seedlings and saplings	1	1.5	7.5	--	0
Nonstocked	4	2.5	2.5	--	0
Ponderosa pine:					
Sawtimber	64	73	90	95	53
Poletimber	23	20	3.5	2.5	41.5
Seedlings and saplings	1	3	2	1	4.5
Nonstocked	12	4	4.5	1.5	1
Douglas-fir:					
Sawtimber	72	72	90	100	0
Poletimber	27	22	8.5	--	0
Seedlings and saplings	0.5	3	--	--	0
Nonstocked	0.5	3	1.5	--	0
Lodgepole pine:					
Sawtimber	34	47	0	0	0
Poletimber	60	45	0	0	0
Seedlings and saplings	5	6.5	0	0	0
Nonstocked	1	1.5	0	0	0
White pines:					
Sawtimber	45	46	100	0	0
Poletimber	52	44	--	0	0
Seedlings and saplings	2	6	--	0	0
Nonstocked	1	4	--	0	0
White spruce:					
Sawtimber	--	100	0	0	100
Poletimber	--	--	0	0	--
Seedlings and saplings	--	--	0	0	--
Nonstocked	--	--	0	0	--
Aspen:					
Sawtimber	7	18	49	44.5	0
Poletimber	80	57	43.5	49.5	0
Seedlings and saplings	13	16	7.5	6	0
Nonstocked	--	--	--	--	0

prefabricated wood products. In recent years, rotary cut spruce veneer has been used in plywood manufacture. Other uses of spruce include specialty items such as violins and pianos and in aircraft construction (Anderson 1956, McSwain et al. 1970). Spruce and fir have not been used much for pulp and paper, but their pulping properties are excellent. Long fibers, light color, and absence of resins permit them to be pulped readily by the sulfite, sulfate, or groundwood processes (Anderson 1956, USDA 1955).

Lodgepole pine wood is generally straight, but uneven grained. The wood is moderately soft, moderately weak in bending and edgewise compression, moderately low in shock resistance, easy to work, easy to glue, and average in paint-holding ability. It holds nails or screws moderately well, shrinks moderately, but seasons easily. It is not durable under conditions that favor decay. Lodgepole pine yields mostly narrow boards and little select grades of lumber, but a high proportion of Grade 3 Common or better (Kotok 1971).

Lodgepole pine was once used primarily for railroad ties, mine timbers,and rough construction lumber. Today much of the lumber is used in light frame construction, particularly as 2- by 4-inch, 8-foot studs. It is especially valued for knotty pine paneling and cabinets because of its uniform color, small tight knots, and dimpled surface. Lodgepole pine is easily pressure treated and is used extensively for fenceposts, corral poles, and transmission and telephone poles. Its pulping properties are good and it can be readily pulped by the sulfate and groundwood processes (Kotok 1971).

THE SPRUCE-FIR TYPE

STAND CONDITIONS

Old-growth spruce-fir forests grow on a wide range of sites with a great diversity of stand conditions and characteristics. This diversity complicates the development of silvicultural systems needed to convert old-growth to managed stands for a variety of uses. For example, spruce-fir forests are the dominant elements in a number of near-climax vegetation associations throughout the central and southern Rocky Mountains, but they do not have the age-class structure of true climax forests. Some stands are clearly single-storied, indicating that desirable spruce forests can be grown under even-aged management. Others are two- or three-storied, and multi-storied stands are not uncommon (Alexander 1973, LeBarron and Jemison 1953, Miller 1970). These later stands may be the result of either past disturbances such as fire, insect epidemics, or cutting, or the gradual deterioration of old-growth stands associated with normal mortality from wind, insects, and diseases. The latter circumstance is especially evident in the formation of some multi-storied stands. On the other hand, some multi-storied stands appear to have originated as uneven-aged stands, and are successfully perpetuating this age-class structure.

The composition of spruce-fir forests varies considerably with elevation. At mid elevations (10,000 to 11,000 ft), these forests are frequently pure spruce in the overstory with fir predominating in the understory. For example, in the central Rocky Mountains spruce commonly makes up 70 percent or more of the overstory basal area, and fir from two-thirds to three-fourths of the understory and advanced reproduction (Alexander 1957a, 1963; Hodson and Foster 1910, Oosting and Reed 1952). This composition in relation to structure has developed under natural conditions because spruce is more exacting in its seedbed requirements and less able to compete with fir under low light intensities common to dense forests. Once established, however, spruce lives longer than fir and is less susceptible to disease (Alexander 1958a, 1958b). Exceptions are in stands attacked by spruce beetles, where fir is the dominant element in both the overstory and understory (see footnote 3).

At higher elevations, spruce may form essentially pure stands while at lower elevations where sites are usually drier, the density of spruce relative to fir may be low. In these latter situations, lodgepole pine is frequently more numerous in the overstory than spruce (see footnote 2).

Advanced spruce and fir reproduction is likely to be older than it appears because the early growth of both is slow. Spruce commonly takes from 20 to 40 years to reach a height of 4 to 5 ft, even under favorable conditions, whereas under a dense canopy, spruces 4 to 6 ft tall may be 75 or more years old (Oosting and Reed 1952). Spruce and fir reproduction suppressed for long periods of time will respond to release, however, and make acceptable growth (Alexander 1973).

PAST CUTTING HISTORY

Limited areas of the original spruce-fir forests were logged in the late 1800's to provide fuel, lumber, and timbers for early mining camps. Cutting on the National Forests dates back more than 50 years, but until the 1950's only relatively small quantities of timber were harvested. Cutting has accelerated rapidly since.

Most cuttings in spruce-fir forests before 1950 in the central and southern Rocky Mountains were of a type that could be collectively called "partial cuttings." They ranged from removal of a few individual trees to removal of all the larger, more valuable trees in the stand. Seedbed preparation was usually limited to the disturbance created by logging, and slash was untreated or lopped. Most skidding was done with horses.

In general, heavy partial cutting — usually considered necessary to make logging profitable — was not successful as a means of arresting stand deterioration or increasing net increment on residual trees. For example, residual stands of spruce-fir in Colorado suffered heavy mortality when 60 percent of the original volume was removed by individual-tree selection (Alexander 1956a, 1963) (fig. 3). Net increment was only about one-third of that in uncut stands. Similar results followed heavy partial cutting elsewhere in the central Rocky Mountains (USDA Forest Service [USDA-FS] 1933),

Figure 3.—Individual-tree selection cutting that removed 60 percent of the volume in spruce-fir. Blowdown losses were heavy because the original dense stand was opened up too much. Fraser Experimental Forest, Colorado.

and in the northern Rockies (Roe and DeJarnette 1965). Even when mortality was not a problem, heavy partial cutting left the older, decadent stands in a shabby condition, with little appearance of permanent forest cover.

Windfall, the principal cause of mortality, increased as the intensity of cutting increased. Low stumpage values and the generally scattered pattern of windfall usually prevented salvage of blowdown after partial cutting. Not only was the volume of windthrown trees lost, but the combination of down spruce and overstory shade provided breeding grounds for spruce beetles.

Partial cutting was successful — in the sense that the residual stand did not suffer heavy mortality — in some spruce-fir stands where large reserve volumes were left in protected locations. In one study in northern Idaho, windfall losses were light after a partial cutting that left a residual stand of 6,000 board ft (fbm) per acre in a sheltered location on deep, well-drained soil (Roe and DeJarnette 1965). On the Grand Mesa National Forest in Colorado, where spruce trees are relatively short and there are no serious wind problems associated with topography, few trees blew down when about 40 percent of the original volume was removed from two-storied stands. In single-storied stands, however, only about 30 percent of the original volume could be safely removed. On the other hand, heavier partial cutting that removed 50 percent or more of the original volumes per acre from spruce-fir forests in the dry "rain shadow" of the Continental Divide on the Rio Grande National Forest did not result in blowdown to the residual stand. However, these two-storied stands were growing on sites where productivity was very low. Individual trees were short, widely spaced, and therefore relatively windfirm before cutting.

There are also numerous examples of early cuttings — between 1910 and 1930 — on many National Forests in Colorado where very light partial cutting — removal of 10 to 15 percent of the stand — did not result in substantial windthrow of residual trees.

Although an overstory tends to favor fir reproduction over spruce, regeneration success of spruce has been acceptable under a wide variety of partial cutting treatments (Alexander 1963, Roe and DeJarnette 1965).

In the early 1950's harvesting shifted to clearcutting. The first clearcuttings were in narrow strips (200 to 400 ft wide) or small patches, with little seedbed preparation or slash disposal (fig. 4). Advanced regeneration was not completely destroyed. In general, windfall losses were less than after heavy partial cutting, and the cutovers were usually adequately re-

Figure 4.—Clearcutting that removed 50 percent of the volume in narrow, alternate strips in spruce-fir. Fraser Experimental Forest, Colorado.

stocked with a combination of surviving advanced and new reproduction (Alexander 1956a, 1957a, 1963, 1966d, 1968; Averill and Andrews 1964). By the late 1950's, the common practice was to clearcut in large blocks, patches, or wide strips. These larger openings were justified as being more effective in controlling spruce beetles and in reducing logging costs. Slash and cull material were either broadcast burned, dozer-piled, or windrowed and burned. Hazards from fire and insects were reduced, but removal of all slash, cull material, and residual trees left the seedbeds devoid of shade, thereby creating a difficult microenvironment for the establishment of either natural or artificial regeneration (Roe et al. 1970, Ronco 1970a). Furthermore, the destruction of advanced reproduction was usually an unnecessary loss of valuable growing stock.

Today, after nearly 20 years of harvesting spruce-fir almost exclusively by clearcutting, there is a shift in cutting practices to either some form of partial cutting or a combination of partial cutting and small cleared openings without complete cleanup of slash and other logging debris (Alexander 1973). This shift was necessary because clearcutting large areas often (1) resulted in adverse visual and environmental impacts, (2) was incompatible with the objectives of other forest uses, and (3) led to regeneration failures.

DAMAGING AGENTS

Windfall

Windfall is a common cause of mortality after any kind of initial cutting in old-growth spruce-fir forests, but partial cutting increases the risk because the entire stand is opened up and therefore vulnerable. Windfall is usually less around clearcuts because only the boundaries between cut and leave areas are vulnerable, but losses can be substantial if no special effort is made to locate windfirm cutting unit boundaries (Alexander 1964, 1967b).

While the tendency of spruce to windthrow is usually attributed to a shallow root system, the development of the root system varies with soil and stand conditions. On medium to deep, well-drained soils, trees have a better root system than on shallow, poorly drained soils. Trees that have developed together in dense stands over long periods of time mutually protect each other, and do not have the roots, boles, or crowns to withstand sudden exposure to wind if opened up too drastically. If the roots and boles are defective, the risk of windthrow is increased. The presence of old windfalls in a stand is a good indicator of lack of windfirmness. Furthermore, regardless of the kind or intensity of cutting, or soil and stand conditions, windthrow is greater on some exposures than others (Alex-

ander 1964, 1967b, 1973). Exposures where windfall risk is below average, above average, or very high have been identified as follows:

Below Average
1. Valley bottoms, except where parallel to the direction of prevailing winds, and flat areas.
2. All lower, and gentle middle north- and east-facing slopes.
3. All lower, and gentle middle south- and west-facing slopes that are protected from the wind by considerably higher ground not far to windward.

Above Average
1. Valley bottoms parallel to the direction of prevailing winds.
2. Gentle middle south and west slopes not protected to the windward.
3. Moderate to steep middle, and all upper north- and east-facing slopes.
4. Moderate to steep middle south- and west-facing slopes protected by considerably higher ground not far to windward.

Very High
1. Ridgetops.
2. Saddles in ridges.
3. Moderate to steep middle south- and west-facing slopes not protected to the windward.
4. All upper south- and west-facing slopes.

The risk of windfall in these situations is increased at least one category by such factors as poor drainage, shallow soils, defective roots and boles, and overly dense stands. Conversely, the risk of windfall is reduced if the stand is open grown or composed of young, vigorous, sound trees. All situations become **very high risk** if exposed to special topographic situations such as gaps or saddles in ridges at higher elevations to the windward that can funnel winds into the area.

Insects

Keen (1952) lists a large number of insect pests of Engelmann spruce. Of these, the spruce beetle (*Dendroctonus rufipennis* (Kirby)) is the most serious. It is restricted largely to mature and overmature spruce, and epidemics have occurred throughout recorded history (Hopkins 1909, Massey and Wygant 1954). The most damaging recorded outbreak was in Colorado from 1939-51, when beetles killed nearly 4 billion fbm of standing spruce (fig. 5). Damaging attacks have been largely associated with extensive windthrow, where down trees have provided an ample food supply needed for a rapid buildup of beetle populations (Massey and Wygant 1954, Wygant 1958). Cull material left after logging has also started outbreaks, and there are examples of heavy spruce beetle populations developing in scattered trees windthrown after heavy partial cutting. The

Figure 5.—Beetle-killed spruce stand. White River National Forest, Colorado.

beetle progeny then emerge to attack living trees, sometimes seriously damaging the residual stand. Occasionally heavy spruce beetle outbreaks have developed in overmature stands with no recent history of cutting or windfall, but losses in uncut stands that have not been subjected to catastrophic windstorms have usually been no greater than normal mortality in old growth (Alexander 1973).

Spruce beetles feed and breed in the phloem layer. The first evidence of attack is the red boring dust from entrance holes that usually accumulates in bark crevices on the boles and around the bases of infested trees. The needles of killed trees usually turn a yellowish green and fall about 1 year after attack, but they may remain green until the second year (Schmid and Beckwith 1971).

Overmature trees are attacked first, but if an infestation persists, beetles will attack and kill smaller diameter trees after the larger trees in the stand are killed. In the central Rocky Mountains, susceptibility of spruce stands in relation to location decreases in the following order: (1) trees in creek bottoms, (2) better stands on benches and high ridges, (3) poorer stands on benches and high ridges, (4) mixed stands, and (5) immature stands (Knight et al. 1956, Schmid and Beckwith 1971). Analysis of past infestations suggests the following characteristics are associated with potential outbreaks: (1) single- or two-storied stands, (2) high proportions of spruce in the overstory, (3) basal area of 150 ft^2 per acre or more in the older and larger trees, and (4) an average 10-year periodic diameter growth of 0.4 inch or less (see footnote 3).

Natural factors such as nematodes, insect parasites and predators, and woodpeckers normally maintain beetle populations at low levels, but generally fail to control populations under outbreak conditions. Extremely low temperature can eliminate beetle infestations, however, if the insect has not developed cold-hardiness. Temperatures of -15° F under the bark will kill nearly all adults, while -30° F will kill the larvae (Schmid and Beckwith 1971). Chemical control is expensive and only a holding action until potentially susceptible trees can be disposed of. In infested stands, or those with potential beetle problems, felling and salvaging attacked or susceptible trees, and disposing of green cull material is the most effective silvicultural control. Partial cutting that removes the larger overmature trees and releases the younger trees is another way to reduce potential insect problems in stands with a good stocking of trees in the smaller diameter classes. "Trap trees" intentionally felled prior to beetle flight are highly attractive, and often provide an effective way of concentrating and trapping spruce beetles (Nagel et al. 1957). After the beetles enter the downed logs, they are usually salvaged, but may be chemically treated or burned (Schmid and Beckwith 1971). Lethal traps in which cacodylic acid is used to prevent brood development in trap trees appears to be a potentially useful refinement to the regular trap-tree approach (Buffam et al. 1973).

The western spruce budworm (*Choristoneura occidentalis* Freeman) is another potentially dangerous insect attacking Engelmann spruce (Whiteside and Carolin 1961). Subalpine fir is attacked by several groups of insects (Keen 1952), the most important of which are the western spruce budworm and the fir engraver (*Scolytus ventralis* Lec.). The western balsam bark beetle (*Dryocoetes confusus* Sw.) may at times be very destructive locally (Stevens 1971).

Diseases

The most common diseases in spruce-fir stands are caused by wood-rotting fungi that result in loss of volume (Hinds and Hawksworth 1966, Hornibrook 1950) and predispose trees to windthrow and windbreak (Alexander 1964, 1967b). In a recent study of cull indicators and associated decay in Colorado, Hinds and Hawksworth (1966) identified the major root and butt fungi in mature to overmature Engelmann spruce as *Fomes nigrolimitatus* (Rom.) Engel., *Pholiota alnicola* (Fr.) Singer, *Polyporus tomentosus* Fr., *Corticium radiosum* (Fr.) Fr., and *Coniophora puteana* (Schum ex. Fr.) Karst. Trunk rots which caused 88 percent of the decay were associated with *Fomes pini* (Fr.) Karst, *Stereum sanguinolentum* (Alb. and Schw. ex. Fr.) Fr., *S. sulcatum* Burt. and *S. chailletii* (Pers. ex. Fr.) Fr. Hinds and Hawksworth (1966) have provided a means of estimating defect in standing spruce based on the average amount of cull. Most cull was associated with specific indicators that were grouped into three classes. Cull deductions for these indicators are shown below:

Indicator type	Decay as a proportion of gross volume (Percent)
1. *Fomes pini* knots or sporophores	81
2. Broken tops with adjacent dead brooms	24
3. Basal wounds, dead broom rusts, dead leader, frost cracks, forks, joined at base, spiketop on trunk wounds	10

Decay in relation to age, diameter, and site quality have been determined for subalpine fir in Colorado (Hinds et al. 1960). Important root and butt rot fungi are *Corticium radiosum* (Fr.) Fr., *Coniophora puteana* (Fr.) Karst, *Armillaria mellea* (Fr.) Quel., *Coniophora olivacea* (Fr.) Karst, *Pholiota squarrosa* (Fr.) Kummer, and *Polyporus tomentosus* Fr. *Stereum sanguinolentum* (Fr.) Fr., *Fomes pini* (Fr.) Karst, and *S. chailletii* (Fr.) Fr. are responsible for most trunk rot.

Spruce broom rust (*Chrysomyxa arctostaphyli* Diet.) and fir broom rust (*Melampsorella caryophyllacearum* Schroet.) are also common in spruce-fir forests. They cause bole deformation, loss of volume, spiketops, and windbreak, and provide infection courts for decay fungi (Peterson 1963).

NATURAL REGENERATION REQUIREMENTS

A supply of viable seed, a suitable seedbed, and an environment compatible with germination and seedling establishment are the basic elements necessary for successful regeneration (Roe et al. 1970). If one of these elements is missing, regeneration fails (fig. 6).

Seed Supply

FLOWERING AND FRUITING

Male flowers of both spruce and fir ripen and pollen is wind disseminated in late spring or early summer. Cones mature and seed ripens from late August to early October the first year (Alexander 1958a, 1958b; USDA-FS 1948).

CONE-BEARING AGE

Although cones have been observed on open-grown spruces and firs when they are about 4 to 5 ft tall and from 15 to 40 years old, seed production does not become significant until the trees are larger and older. The most abundant crops in natural stands are produced on healthy, vigorous, dominant trees 100 to 250 years old (Alexander 1958a, 1958b; USDA-FS 1948).

TIME OF SEEDFALL

Natural seedfall in spruce stands begins in early September and continues through the winter, but only minor amounts of seed fall before mid-September. In 1 year on the Fraser

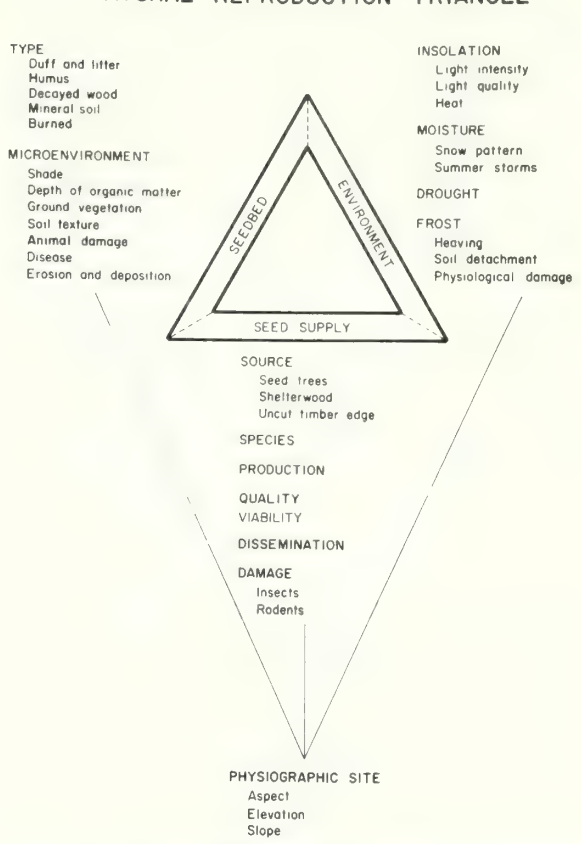

Figure 6.—Factors affecting spruce seedling survival and establishment (Roe et al. 1970).

Experimental Forest in Colorado, about half of the total sound seed was released before the end of September.[7] In a good seed year in the Intermountain Region, from two-thirds to three-fourths of the total sound seed was released by October 20 on two areas, but only about one-third of the total sound seed was released by that date on a third area (Roe 1967).

Subalpine fir seedfall begins in early September and is usually completed by the end of October (Alexander 1958b).

CONE-CROP PREDICTABILITY

The ability to estimate the size of the cone crop well in advance would be important to the forest manager, because it would provide the basis for scheduling harvesting operations, seedbed preparation for natural reproduction,

[7] *Unpublished data on file with study FS-RM-1201.24, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

and seed collection (Dobbs 1972). Several ways have been suggested as a means of estimating potential cone crop size for other species, but no method has been developed for spruce.

PRODUCTION AND PERIODICITY

Engelmann spruce is rated a moderate seed producer, and seed crops vary considerably from year to year. Infrequent seed crops means that natural reproduction cannot be expected every year.

In an early study in Colorado, average annual seed production on the White River Plateau for an 18-year period (1914-31) was 83,000 sound seeds per acre, while on the Uncompaghre Plateau, annual seed production for a comparable 15-year period (1914-28) averaged 350,000 sound seeds per acre (USDA-FS 1933). Good seed crops (100,000 or more sound seeds per acre) were produced on the White River only at 5- to 7-year intervals, with complete failures about every 2 years. On the Uncompaghre, good crops were produced every 2 to 4 years, with complete failures at about 3-year intervals. In a study on the Fraser Experimental Forest in Colorado, annual seed production averaged only 32,100 sound seeds per acre during the period 1956-65 (Alexander 1969). Only one good and two moderate (50,000 to 100,000 sound seeds per acre) crops were recorded. Seed production was also observed on five National Forests in Colorado for the period 1961-67.In one year (1967) a bumper seed crop was produced on all areas. Seed production, varying from 845,000 to 5,340,000 sound seeds per acre, was the highest ever recorded in the central Rocky Mountains (Ronco and Noble 1971). In the other years of the study, some seed was produced each year, but good crops occurred only once in 4 to 5 years on three of the areas, and in 2 of 6 years on the other two areas (Ronco 1970b). Furthermore, these good crops did not occur in the same years on all areas.

Similar results for spruce have been reported from the northern Rocky Mountains. Boe (1954) analyzed cone crops in Montana between the years 1908 and 1953. He reported that 22 crops observed during the 45-year period west of the Continental Divide were rated as 5 good, 8 fair, and 9 poor. East of the Divide, seed production was poorer; only 2 good, 4 fair, and 15 poor crops were reported for a 21-year period. Seed production in 1952 in western Montana was estimated at 953,000 sound seeds per acre (Squillace 1954), but this was in a bumper year. Seed crops in the other 4 years of record were failures. Seed production in a good year (1964) on three areas in the Intermountain Region ranged from 200,000 to 2 million sound seeds per acre (Roe 1967). Seed production in the other 4 years of observation were also rated failures.

Subalpine fir seed production has not been studied in the central and southern Rocky Mountains. Elsewhere in the Rocky Mountains, it has been rated a prolific seed producer, with good crops borne every 3 years with light crops in between (LeBarron and Jemison 1953, USDA-FS 1948). In one study in the Cascade Mountains of Washington and Oregon, fir produced light to very heavy cone crops about every 3 years with failures in the intervening years (Franklin 1968). Observations in the central Rocky Mountains indicate that fir is not that good a seed producer, and failures are more common than good seed years.

SEED QUALITY

Variability in seed quality accentuates differences in seed production. The proportion of sound seed is usually highest in years of highest seed production. In the central Rocky Mountains, 70 to 90 percent of the seed produced in the bumper seed year of 1967 was sound.[8] In years of moderate to good crops, 30 to 50 percent were sound, and in other years, 10 to 30 percent were sound.

DISPERSAL

Spruce seed is light, averaging about 135,000 seeds per pound, and disperses long distances. In one study in Colorado,[8] as many as 96,000 sound seeds per acre were dispersed as far as 400 ft from standing timber into a clearcut block. In western Montana, significant quantities of seed (60,000 sound seed per acre) were dispersed as far as 600 ft from timber edge into a large clearcut block (Squillace 1954). These dispersals occurred only during a bumper (1952) and record (1967) seed year, however (Ronco and Noble 1971, Squillace 1954). Seedfall into cleared openings in Colorado that varied from about 130 to 850 ft wide, diminished as distance from seed source increased; most seeds fell within 100 to 150 ft of standing timber (Alexander 1969, Ronco 1970b, Ronco and Noble 1971). Prevailing winds influenced the pattern of seedfall on areas larger than 200 ft wide. In years of significant seed production, about half of the total number of sound seeds dispersed fell within 150 ft of the windward timber edge. Seedfall then

[8] *Unpublished data on file with study FS-RM-1201.13, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

liminished steadily as distance increased to about two-thirds of the way across the openings. At this distance the average number of sound seeds falling was about 10 percent of the number released in the uncut stands. Beyond this point, seedfall gradually increased toward the leeward timber edge (fig. 7).

In the Intermountain and Northern Rocky Mountain Regions, spruce seed dissemination on four areas in good seed years also diminished from timber edge into openings (Roe 1967). Seed was dispersed in significant quantities (0.5 to nearly 5 percent of the total released under the uncut stand) as far as 660 ft where a heavy seed source was present, (193 ft^2 of basal area in Engelmann spruce trees 10.0 inches d.b.h. and larger), but the dispersal winds were too variable to show definite directional patterns. Lighter seed sources, 70 ft^2 of basal area or less, dispersed fewer seeds for shorter distances. Smaller openings are required with lighter seed sources to insure adequate seedfall on all parts of the opening, otherwise the areas beyond the reach of adequate natural seeding must be artificially reforested (Roe 1967).

Just because seed can be dispersed long distances is not enough. Large quantities of seed will not restock harsh or incompatible environments (Roe et al. 1970). For example, seedfall that averaged 1.8 million sound seeds per acre over the entire opening on one area in Colorado did not result in adequate restocking because of unfavorable seedbeds and adverse environmental conditions: intense solar radiation and high temperatures, low temperatures and frost heaving, and drying winds (Ronco and Noble 1971).The effective seeding distance, defined by Roe et al. (1970) as the distance over which sufficient sound seed is dispersed to stock an area to an acceptable level under prevailing conditions, is more meaningful than mere seed dispersal distance.

A current study[9] of field germination on the Fraser Experimental Forest in Colorado has indicated that, on north slopes under favorable seedbed and environmental conditions (shaded, mineral soil), at least 20,000 sound seeds per acre are needed to provide 1,000 seedlings surviving at the end of the first growing season. That seedfall is not likely to occur beyond about 300 ft from a windward seed source except in years of bumper seed production. Furthermore, seedling mortality will continue to reduce initial first-year stocking for at least 5 years. Therefore, adequate restocking is not likely to result

[9]*Unpublished data on file with study FS-RM-1201.20, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

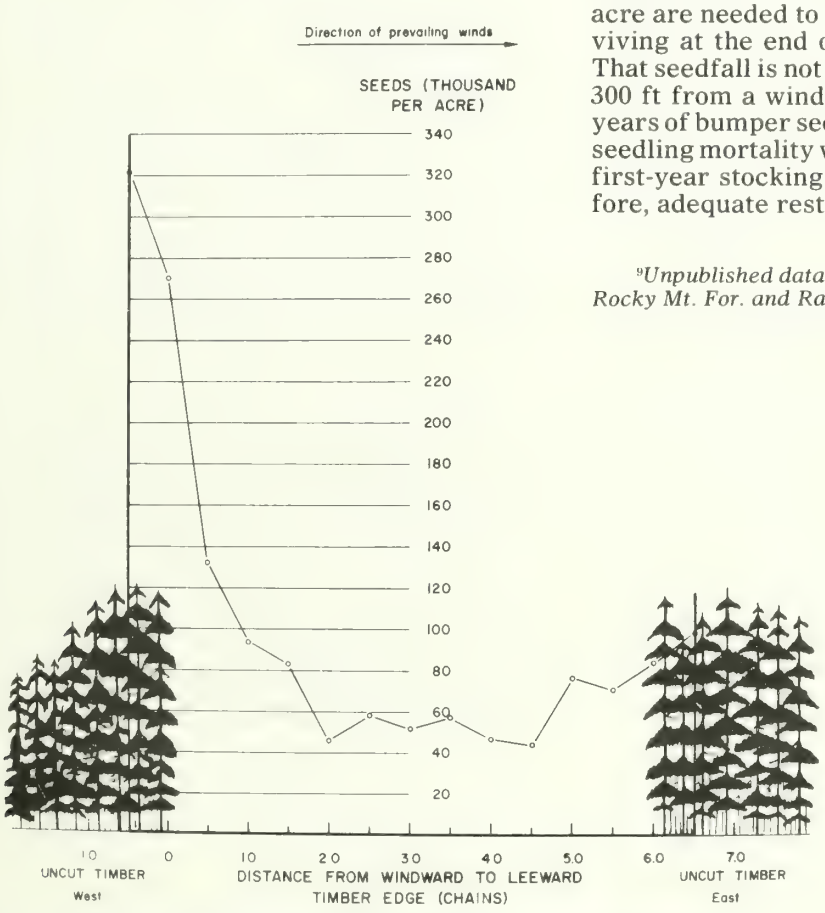

Figure 7.—Total 10-year Engelmann spruce seedfall into clearcut openings in relation to distance from windward timber edge.

from only one good seed crop. This suggests that the maximum width of opening that can restock over a period of years under favorable conditions is about 450 ft or five to six times tree height. On south slopes under the same seedbed and environmental conditions, at least 100,000 sound seeds per acre will be required to provide 1,000 first-year seedlings. Effective seeding distance is about 100 ft from the windward seed source. On the other hand, on north slopes 200,000 sound seeds per acre will be required to provide 1,000 first-year seedlings on unprepared and unshaded seedbeds, while no amount of seed will restock these seedbeds on south slopes (see footnote 9). Under average conditions in the Rocky Mountains, the distance of effective seed dispersal is likely to be 150 ft or less (Alexander 1969, Jones 1967, Roe and Schmidt 1964, Ronco 1970b).

Effective seeding distance may be greater in the northern than in the central Rocky Mountains. In one study in northern Idaho, a peripheral strip 660 ft wide around a large patch cutting was restocked naturally (Roe and DeJarnette 1965). Roe et al. (1970) have suggested that an effective seeding distance of 660 ft may be possible on northerly aspects with about 200 ft^2 of basal area in seed trees in the uncut timber edge, but only 200 to 400 ft is likely on south slopes. Effective seeding distances with a light seed source, 70 ft^2 of basal area or less, will vary from 0 to 200 ft on north slopes and 0 on other aspects.They concluded that the longer a favorable seedbed persists the greater the effective seeding distance.

Subalpine fir seed is larger than spruce, averaging about 37,500 to the pound (Alexander 1958b, USDA-FS 1948). Practically all seed is wind disseminated, but there are no data on dispersal distances.

SOURCE

There are several ways of providing a seed source for both spruce and fir. In cleared openings, the principal seed source is the trees left standing around the perimeter of the opening. Minor amounts of seed are available from the smaller unmerchantable trees left on the area, and some seed is also produced by the trees cut on the area. On partially cut areas, the residual trees are the principal seed source, but some seed is produced by trees cut on the area. One of the significant considerations in the kind of seed source to leave is resistance to windthrow. Situations and conditions where windfall risks were high, above average, and below average around the margins of cleared openings have been identified in Colorado, and recommendations developed for locating windfirm boundaries on clearcut units (Alexander 1964, 1967b). These recommendations have been modified to identify the kinds of trees and residual volumes that can be successfully retained in partial cutting for different stand conditions and windfall risk situations (Alexander 1973).

VIABILITY

The viability of spruce is rated both good (average germinative capacity is about 70 percent the first year) and persistent (average germinative capacity 30 to 50 percent after 5 years) if stored properly (Alexander 1958a, USDA-FS 1948, Van Dersal 1938).Spruce does not normally require pretreatment to break dormancy, and germinative capacity is not improved by stratification (Curtis 1958). Under natural conditions, seed overwinters under the snow and germinates the following spring. Occasionally some germination is delayed until the second year (Ronco 1967, see also footnote 9).

Subalpine fir seed viability is rated only fair (average germinative capacity is 38 percent) and the vitality transient (Alexander 1958b, USDA-FS 1948, Van Dersal 1938). However, observations and limited studies in the Rocky Mountains indicate that germinative capacity is often less than 30 percent (Shearer and Tackle 1960). Some lots of stored seeds exhibit embryo dormancy, which can be broken by stratification in moist sand or peat at 41° F for 60 days (USDA-FS 1948). Under natural conditions, fir seeds lie dormant under the snow and germinate the following spring.

SEED LOSSES

Observations on the Fraser Experimental Forest indicated that a substantial part of the 1972 spruce seed crop was lost before seedfall to cone and seed insects.[10] A number of cone and seed insects of spruce and fir have been identified by Keen (1958), but their relative importance, frequency of occurrence, and the magnitude of losses are not known.

Pine squirrels (*Tamiasciurus hudsonicus fremonti* Audubon and Bachman) are a major consumer of spruce and fir cones and seeds, as evidenced by the large caches common to spruce-fir forests. These caches have been the principal source of seed for reforestation.

[10]*Personal communication with Daniel L. Noble, Forestry Technician, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

After seed is shed to overwinter under the snow, small mammals are the principal source of seed losses. The most important seedeaters include deer mice (*Peromyscus maniculatus* (Wagner)), red-backed mice (*Clethrionomys gapperi* (Vigors)), mountain voles (*Microtus montanus* (Peale)), and western chipmunks (*Eutamias minimus* Bachman). All spruce-fir forests support populations of these small mammals, and any disturbance that initiates understory plant succession favors a buildup of populations, particularly if slash and other down material is present to provide cover. Undoubtedly these mammals eat considerable seed, but the magnitude of losses is not known for the central and southern Rocky Mountains, and results from studies elsewhere are conflicting. In western Montana, for example, spruce seedling success was little better on protected than unprotected seed spots (Schopmeyer and Helmers 1947). On the other hand, protection of seed from rodents was essential to spruce and fir regeneration success in central and southern British Columbia (Prochnau 1963, Smith 1955).

Factors Affecting Germination

Viable seeds of spruce and fir that survive overwinter normally germinate following snowmelt in June or early July in the central Rocky Mountains, when seedbeds are moist and air temperatures at least 45° F. On the Fraser Experimental Forest in Colorado, field germination of spruce seeds has ranged from 0 to 28 percent, depending upon seedbed, weather, and aspect (see footnote 9).

Seedbed is one of the keys to spruce germination success (Roe et al. 1970). Germination is usually better on exposed mineral soil than other seedbed types because of more stable moisture conditions (Clark 1969, Day 1964, Day and Duffy 1963, Roe and Schmidt 1964,see also footnote 9). Germination is often good on mineral soil with incorporated organic matter if a constant supply of moisture is available (Clark 1969; Day 1963, 1964). Germination on burned seedbeds has been variable. Success has been associated with the severity of burn and the depth of loose ash (Clark 1969, Roe et al. 1970, USDA-FS 1943). The natural forest floor, duff, litter, and undecomposed humus are generally poor seedbeds even when moist because seeds cannot absorb sufficient water to germinate (Barr 1930, Smith 1955). Germination may be high on decayed wood (Day 1964, Day and Duffy 1963), but without overhead shade many of these seedlings die when the seedbed dries out (Roe et al. 1970).

The effectiveness of the seedbed is influenced by such factors as weather, shade, and soil texture that operate primarily through their effects on moisture and temperature. Dead shade may increase germination by reducing temperatures, thereby conserving moisture. Low temperatures on shaded seedbeds in the spring following snowmelt may delay germination, however, so that by the time seedbeds are warm enough they are too dry. Germination can also be delayed if precipitation is low or irregular in June or early July following snowmelt. Exposed seedbed surfaces are rapidly dried out and heated to high temperatures during periods of clear weather. Few seeds can imbibe sufficient water to germinate, and most newly germinated seedlings are killed by either drought or stem girdle (Day 1963, 1964; Roe et al. 1970). If germination is delayed until the late summer rains, the late-germinating seedlings are unable to harden off before the onset of cold weather (Ronco 1967, see also footnote 9). Ronco (1967) also found that germination followed definite storm periods.

Alexander and Noble (1971) studied the effects of amount and distribution of watering treatments — selected to represent precipitation patterns and temperatures likely to occur at 10,500 ft elevation on the Fraser Experimental Forest in Colorado — on the germination of spruce in the greenhouse. They concluded that, under favorable seedbed and environmental conditions: (1) more seedlings would emerge with frequent showers than with one or two larger storms when monthly precipitation is 1 inch or less, and (2) when monthly precipitation averages 1 inch or more, germination is completed in a relatively short time with frequent showers, whereas seedlings will emerge throughout the growing season if precipitation falls in only one or two storms.

Noble (1972) found no differences in spruce germination on two soil types in a greenhouse study in Colorado, but both soils were gravelly sandy loams. On the other hand, striking differences were found in germination on two soil types in western Montana (Roe et al. 1970). Seeds were sown in the spring on a droughty sandy loam and a black, moderately heavy loam soil that retained a high moisture content throughout the growing season. More than nine times as many seedlings germinated on the heavier soil. Apparently, rapid surface drying limited moisture for germination on the sandy soil.

Germination of subalpine fir is usually good on mineral soil seedbeds (Clark 1969, USDA-FS 1943). Fir is less exacting in its seedbed requirements than spruce, and will germinate and become established on a wider variety of seedbeds (Alexander 1958b; Day 1963, 1964).

Factors Affecting Initial Survival and Seedling Establishment

Most spruce seedling mortality occurs during the first growing season, but losses can be substantial during the first 5 years after germination (Ronco 1967, 1970b; see also footnote 9). The first growing season is considered here as the period of initial survival, and the second through the fifth growing seasons as the time of seedling establishment.

INITIAL ROOT GROWTH

The rate of root growth is an important determinant of initial survival of spruce seedlings. The further the root penetrates the soil, the better chance the seedling has of surviving drought, frost heaving, and erosion. Critical rooting depth depends upon seedbed type, weather, and soil properties.

First-year spruce seedlings (fig. 8), field grown on mineral soil seedbeds under partial shade on the Fraser Experimental Forest in Colorado, have a rooting depth of 3 to 4 inches, with a total root length of 5 inches (Noble 1973b). In an earlier study in the central Rocky Mountains, the root length of vigorous 1-year-old spruce seedlings averaged about 2.75 inches on seedbeds where the depth of humus was about 1 inch (Roeser 1924). In eastern Arizona, average first-year spruce root penetration was 2.7 inches on shaded mineral soil (Jones 1971). In the northern Rocky Mountains and British Columbia, first-year root penetration of spruce seedlings under field conditions is only about 1.5 inches (Roe et al. 1970, Smith 1955).

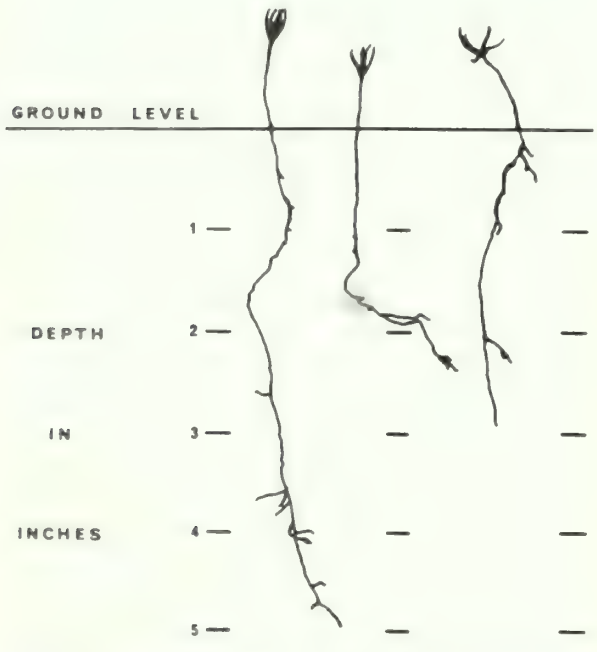

Figure 8.—Engelmann spruce seedling roots at the end of the first growing season.

No comparable data are available for subalpine fir in the central Rocky Mountains, but first-year root penetration of its variety, corkbark fir, in Arizona averaged 3.4 inches (Jones 1971). In British Columbia, first-year root length of subalpine fir averaged 2.7 inches (Eis 1965).

SEEDBED TYPE

In the undisturbed forest, spruce seedlings become established on a variety of seedbeds: duff, litter, partially decomposed humus, decaying and moss-covered wood, and on mounds of mineral soil upturned by windthrown trees (Alexander 1958a, Dobbs 1972). These same seedbeds are available after logging, with some additional mineral soil and mineral soil mixed with humus. Removal of the overstory, however, will produce new microhabitats, many of which will be unfavorable to initial survival and seedling establishment. Seedbed preparation is one way to modify limiting environmental factors sufficiently to enable seedlings to survive (Roe et al. 1970).

Spruce seedling survival and establishment after logging in the central Rocky Mountains have generally been better on prepared mineral soil seedbeds than on other seedbed types (USDA-FS 1943, see also footnote 9), because mineral soil provides a more stable moisture source than other seedbed types (Smith 1962). Exceptions have been on south slopes, where shade has been more important to initial survival than the seedbed type (see footnote 9). In some instances, subalpine fir has established more readily on mineral soil, while in others more fir seedlings were found on undisturbed seedbeds (Alexander 1966d, USDA-FS 1943).

In the Intermountain Region, Roe and Schmidt (1964) found that mechanically exposed mineral soil was superior to all other seedbeds for initial survival and establishment of spruce seedlings. Decayed wood, the natural forest floor, and undisturbed duff were poor seedbeds. In northern Idaho, spruce stocking after 5 years was better on scarified seedbeds where 40 percent or more of the area was exposed mineral soil than on the natural forest floor or areas where scarification had exposed only about 20 percent of the surface in mineral soil (Boyd and Deitschman 1969). In southwest-

ern Alberta on the Crowsnest Forest, spruce seedling establishment was best on decayed wood, but success was associated with moist sites (Day 1963, Day and Duffy 1963).

Spruce seedling establishment on burned seedbeds has been variable. Stocking was poor or nonexistent in the central Rocky Mountain and Intermountain Regions on burned piles and windrows where burning left layers of loose ash several inches deep, or generated such great heat that rocks were fractured (Roe and Schmidt 1964, USDA-FS 1943). Under these conditions, burned seedbeds are not likely to support any plants for long periods of time (Roe et al. 1970). On the other hand, Boyd and Deitschman (1969) found that spruce stocking on seedbeds 5 years after prescribed burning was as good as on scarified seedbeds where 40 percent or more of the area was exposed mineral soil.

The length of time seedbed treatment remains effective also varies. On the Fraser Experimental Forest in Colorado, scarified seedbeds on light-textured gravelly, sandy, loam soils with a vaccinium ground cover were still discernible 8 to 10 years after treatment, whereas scarified seedbeds on more heavily textured soils with a ground cover of grasses and sedges were largely obliterated in 3 years (Alexander 1969). Seedbeds on the latter soils were not receptive long enough for seedlings to become established. Mechanically scarified and prescription-burned seedbeds did not last longer than about 5 years in northern Idaho, but that was sufficient time for seedlings to become established (Boyd and Deitschman 1969). The best results with natural or artificial seeding on scarified seedbeds in the interior of British Columbia were obtained in the first and second growing seasons after seedbed treatment (Aridge 1967).

Spruce seedling survival and establishment on natural seedbeds are limited by the depth of organic matter, whether it is partially decomposed L, F, and H layers or an accumulation of litter, duff, or other debris (Roe et al. 1970). Although germination may have been good, few spruces became established in the Intermountain Region where the depth of organic matter on the seedbed exceeded 2 inches (Roe and Schmidt 1964). Poor establishment was attributed to first-year root penetration that was too shallow to keep pace with the rate at which the seedbed dried out during the summer. Even with a deeper first-year root penetration, seedlings in the central Rocky Mountains do not become established readily on seedbeds covered with heavy layers of duff, litter, or partially decomposed humus (Roeser 1924).

CLIMATE

The climate of the Rocky Mountain subalpine is characterized by extremes in insolation, temperature, and moisture (Alexander 1958a, 1958b). Some of these extremes limit regeneration success.

Insolation

Light intensity and total solar radiation are high where spruce grows. Solar radiation in the high mountains of Colorado can be as high as 2.2 cal/cm^2/m on a clear day with scattered cumulus clouds (Gates and Janke 1966, Spomer 1962). On cloudless days, daily and weekly mean maximums of about 1.9 cal/cm^2/m throughout the summer have been reported (Spomer 1962). Maximum air temperatures at 10,000 ft elevation rarely exceed 78° F, however (Roe et al. 1970).

Light is essential to seedling survival, but spruce does not establish readily in the open at high elevations in the Rocky Mountains. Seedlings develop a chlorotic appearance that is unrelated to nitrogen content (Ronco 1970c) and subsequently die. High light intensity (visible light can be as high as 13,000 footcandles (fc) from shortly after sunrise to shortly before sunset) is one of the factors contributing to the mortality of seedlings planted in the open (Ronco 1970d). Mortality can be reduced by shading planted seedlings (Ronco 1961b, 1970a, 1972). Ronco (1970d) also found that photosynthesis was higher for shaded than unshaded seedlings. He suggests that solarization — a phenomenon by which light intensity inhibits photosynthesis — leads to irreversible tissue damage and subsequent death of seedlings.

More natural seedlings were also established in the Intermountain Region in the shade of nonliving material than elsewhere (Roe and Schmidt 1964). Shade not only reduced light intensity, but lowered temperatures and conserved moisture, thereby improving the microenvironment for seedling survival and establishment.

On the other hand spruce seedlings cannot compete with subalpine fir in the low light intensities commonly found in dense natural stands.

Temperature

Engelmann spruce is restricted to high elevations because of low tolerance to high air temperatures (Bates 1923, Hellmers et al. 1970).

However, solar radiation at high elevations heats exposed soil surfaces and increases water losses from both seedlings and soil by both transpiration and evaporation. Drought or heat girdling may cause mortality, especially among first-year seedlings (Roe et al. 1970).

Tree seedlings in the succulent stage are particularly susceptible to stem girdling. The cortex is killed by a temperature of 130° F, but prolonged exposures to lower temperatures may also be lethal. On the Fraser Experimental Forest, soil surface temperatures have exceeded 150° F in the open on both north and south slopes at 10,500 ft elevation in the month of June (see footnote 9). Maximum air temperature during this period did not exceed 78° F. In western Montana, at lower elevations, soil surface temperatures exceeded 160° F on gentle north slopes several times during one summer (Roe et al. 1970). Early shade protection improved survival of newly germinated spruce seedlings; 30 to 50 percent of the seedlings were lost to heat girdling on unshaded plots, compared to 10 percent on shaded plots. Day (1963) studied heat and drought mortality of newly germinated spruce seedlings in southwestern Alberta, and found that when water was excluded nearly three-fourths of the mortality on four different unshaded seedbed types was caused by heat girdling. Surface temperatures as low as 113° F caused heat girdling, but losses were not high until soil surface temperatures were above 122° F. Shading reduced heat girdling on all seedbed types. Soil surface temperatures in excess of lethal levels for spruce seedlings, especially on burned seedbeds, have been reported in British Columbia (Smith 1955).

The growing season is short at 10,000 ft elevation in the Rocky Mountains, and frost can occur any month of the growing season (Alexander 1958a, Ronco 1967). Frost is most likely to occur in depressions and cleared openings because of cold air drainage and radiation cooling. Newly germinated spruce seedlings are susceptible to damage from early fall frosts. In a greenhouse and laboratory study, new seedlings did not survive temperatures as low as 15° F until about 10 weeks old (Noble 1973a). Terminal bud formation began at 8 weeks; buds were set and needles were mature at 10 to 12 weeks after germination.

After the first year, seedlings are most susceptible to frost early in the growing season when tissues are succulent. Shoots are killed or injured by mechanical damage resulting when tissue freezes and thaws. Frost damage has been recorded in most years in Colorado (Ronco 1967). In light frost years damage was minor, but heavy frosts either damaged or killed all new shoots of open-grown seedlings (fig. 9).

Figure 9.—Frost damage to an open-grown, planted Engelmann spruce seedling.

Furthermore, the loss of new shoots was at the expense of stored food reserves. Frost damage was nearly eliminated by shading the seedlings (Ronco 1967).

In the early fall, the combination of warm daytime temperatures, nighttime temperatures below freezing, and saturated soil unprotected by snow are conducive to frost heaving. On the Fraser Experimental Forest, these conditions have occurred in 2 out of the past 5 years (see footnote 9). Frost heaving has been one of the principal causes of first-year seedling mortality on scarified seedbeds on north slopes. Furthermore, seedlings continue to frost heave after four growing seasons. Shading has reduced losses by reducing radiation cooling.

Moisture

The moisture condition of the seedbed during the growing season largely determines first-year seedling survival.On some sites in the central Rocky Mountains, summer drought is responsible for substantial first-year mortality, especially in years when precipitation is low or irregular. On the Fraser Experimental Forest, drought and desiccation have caused more than half of the first-year seedling mortality in 4 years of observation on south slopes (see footnote 9). On north slopes during the same period, drought has accounted for only about one-third of first-year seedling mortality. On the other hand, frequent watering during dry summers did not increase first-year survival of planted spruce in central Colorado (Ronco 1967).

In the northern Rocky Mountains, late spring and early summer drought is a serious threat

most years to first-year seedlings. In western Montana, all seedlings on one area were killed by drought in a 2-week period in late summer when their rate of root penetration could not keep pace with soil drying during a prolonged dry period (Roe et al. 1970). Late spring and early summer drought is also a serious cause of seedling mortality in the Southern Rockies.

The moisture provided by precipitation during the growing season is particularly critical to the survival of seedlings during the first year. Alexander and Noble (1971) studied the effects of amount and distribution of watering treatments on seedling survival in the greenhouse. Treatments simulated common summer precipitation patterns in north central Colorado. They concluded that, under favorable seedbed and environmental conditions: (1) At least 1 inch of well-distributed precipitation is needed monthly before seedlings will survive drought; (2) with this precipitation pattern, more than 1.5 inches of monthly rainfall is not likely to increase seedling survival; but (3) few seedlings will survive drought with less than 2 inches of rainfall monthly when precipitation comes in only one or two storms.

Summer precipitation may not always benefit seedling survival and establishment. Summer storms in the Rocky Mountains may be so intense that much of the moisture runs off, especially from bare soil surfaces. Moreover, soil movement on unprotected seedbeds buries some seedlings and uncovers the roots of others (Roe et al. 1970).

SOIL

Throughout the Rocky Mountains, spruce and fir grow on a wide range of soils — described by Johnson and Cline (1965) and Retzer (1962) — but there is little information about the soil requirements for regeneration. Noble (1972) compared first-year spruce seedling survival and growth on two soils in the greenhouse. One soil — Bobtail gravelly sandy loam — is a Sols Bruns Acides which developed in place under a mixed spruce-fir-lodgepole pine stand from mixed schists and gneisses that were metamorphosed from granitic rock. The other soil — Darling gravelly sandy loam — is a Podzol developed in place under a spruce-fir stand from coarse-textured materials weathered from mixed schists and gneisses. The Bobtail soil crusted and compacted when watered — as it did in the field — and root penetration was significantly less than on Darling soils. Consequently, 1.5 inches of water well-distributed monthly was required to obtain survival on Bobtail soils, whereas significant survival was obtained on Darling soils with 1 inch of water well distributed monthly. Top growth and total dry matter production after 24 weeks were about the same on both soils. Alexander (1958a) reported that spruce generally establishes and makes good growth on moderately well-drained silt and clay loam soils developed in place from volcanic and fine sedimentary rock, and on alluvial soils developed from a variety of parent materials, because these soils do not dry out rapidly. Spruce does not establish or grow as well on shallow, dry, coarse-textured sands, gravels, heavy clay surface soils, or saturated soils.

No information is available on the range of pH tolerated by spruce and fir, or their nutrient requirements.

High-intensity storms and runoff from snowmelt cause erosion that results in seedling mortality on mineral soil seedbeds (Roe et al. 1970). In the central Rocky Mountain and Intermountain Regions, seedlings are destroyed by either scouring that uncovers the roots or deposition that buries the seedlings (Roe and Schmidt 1964, see also footnote 9).

DISEASES

Newly germinated seedlings are killed by damping-off fungi (Ronco 1967, see also footnote 9). Losses normally occur early in the growing season before seedlings cast their seedcoats, and can be serious on all seedbed types if they remain damp for long periods of time. Damping-off was responsible for 17 percent of the first-year seedling mortality in central Colorado on both mulched and unmulched mineral soil seedbeds in a year when the growing season was particularly wet (Ronco 1967). Damping-off was the principal cause of mortality of newly germinated seedlings in the greenhouse when they were watered sufficiently to keep the soil surfaces from drying (Alexander and Noble 1971, Noble 1972).

Snowmold fungus (*Herpotrichia nigra* Hartig) occasionally damages or kills both natural and planted seedlings (Ronco 1967, 1970a; see also footnote 9). Losses are most severe when seedlings remain under the snow too long, as in years of heavy snowfall or when weather retards snowmelt in the spring, or in depressions where snow normally accumulates and melts slowly.

ANIMAL DAMAGE

A number of animals damage and kill young seedlings. Haig et al. (1941), Roe et al. (1970),

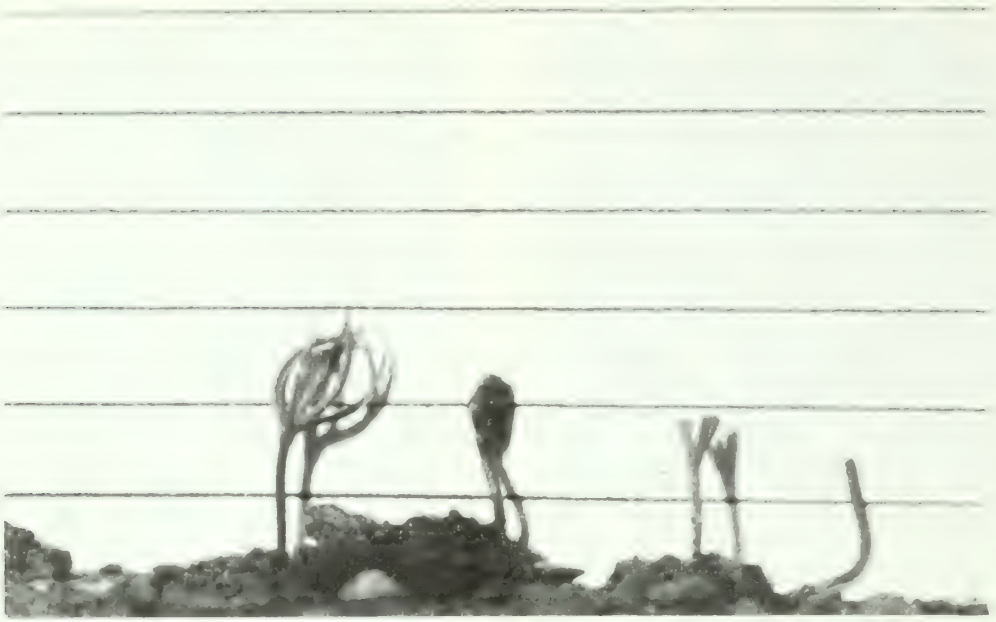

Figure 10.—Clipping damage to newly germinated spruce seedlings by juncos. Fraser Experimental Forest, Colorado.

and Ronco (1967) have suggested that mice consume cotyledonous seedlings as well as ungerminated seeds. Those workers based their conclusions on observations of seedlings that were clipped shortly after germination while seedcoats were still attached, but there is no documented evidence of mice actually doing the damage. A study by Noble and Shepperd (1973) indicates that the grey-headed junco (*Junco caniceps* Woodhouse) is probably responsible for clipping mortality and damage in the central Rocky Mountains previously attributed to mice (fig. 10). Established seedlings are not immune, however, to rodent damage. During some winters, established seedlings are debarked and killed by mountain voles, and mountain pocket gophers (*Thomomys talpoides* (Richardson)) periodically cause heavy mortality to spruce plantations up to 3 to 4 years after planting (Ronco 1967, 1970a).

The extremely small size of young spruce seedlings makes them especially vulnerable to damage by grazing and browsing animals. In western Montana, cattle — in one trip through a seedling survival study area — trampled or killed 10 percent of the marked first-year spruce seedlings. They were either buried or kicked out of the ground (Roe et al. 1970). Trampling damage by cattle and big-game animals is likely to be more severe on prepared seedbeds, especially if they have been plowed or disked, because the ground provides easy travel routes. Spruce is seldom eaten by these animals, but young subalpine fir is frequently browsed heavily by big-game.

GROUND VEGETATION

Understory vegetation can be either a benefit or a serious constraint to spruce seedling survival and establishment (Alexander 1966d, Day 1964, Ronco 1972). Observations of natural and artificial regeneration on several areas in the central Rocky Mountains have indicated spruce seedlings become established more readily on sites protected by such plants as willow (*Salix* spp.), shrubby cinquefoil (*Potentilla fruticosa* (L.) Rydb.), fireweed (*Epilobium angustifolium* L.), and dwarf whortleberry (*Vaccinium* spp.) than in the open. These plants shade seedlings without seriously depleting soil moisture. In contrast, mortality has been recorded when seedlings started near clumps or scattered individual plants of grasses or sedges, or herbaceous plants such as bluebells (*Mertensia* spp.) which spread to form a dense, solid cover with roots completely occupying the soil. Death is due to root competition for moisture and smothering by cured vegetation compacted under dense snow (Ronco 1972). The probability of regeneration success on an area with a complete cover of dense sod of grasses and sedges is low. In Utah, Pfister (1972) rated the environment for spruce regeneration success as severe in habitat types where the understory was

dominated by *Ribes montigenum*, and moderate where the understory was dominated by *Berberis repens*. He concluded that natural regeneration success could be obtained in these habitat types only by maintaining a continuous forest cover.

SITE QUALITY

The evaluation of site quality is essential to the land manager as a means of identifying and intensifying management practices where timber production has the greatest potential.

Conventional Determination

Site index is the only method now available for estimating the potential productivity of spruce-fir forests in the central and southern Rocky Mountains. Alexander (1967a) prepared curves of the height and age relationship of dominant spruces that are suitable for estimating site index at base age 100 years in spruce-fir stands where age at breast height is at least 20 years (fig. 11). Data for these curves came from 2,100 dominant spruces with annual ring sequences showing no evidence of past suppression, on 350 plots in southern Wyoming and throughout Colorado. These plots were selected to represent the available range in density, site quality, and age.

Height measurements to the nearest foot and age at breast height from increment borings of at least six dominant spruce trees should be averaged when the site index curves are used. This will provide an integrated site index value that applies over the area occupied by trees aged and measured. Little improvement in sampling error is gained by measuring more than six trees (Brickell 1966).

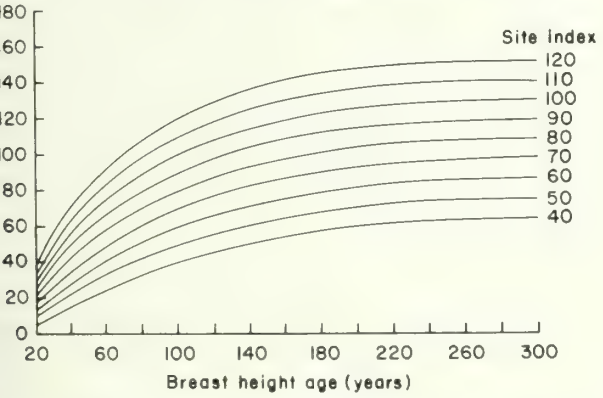

Figure 11.—Site index curves for Engelmann spruce in the central Rocky Mountains. Base age: 100 years, breast height.

In addition to being dominants, trees selected for measurement should meet the following criteria:

1. Even-aged — not more than a 20-year spread in the age of the dominant stand.
2. At least 20 years old at breast height — preferably 50 years old or older, because of the variability in height growth of trees on the same site at ages 20 to 50 years.
3. Show no visible evidence of crown damage, such as broken or forked tops, disease, or excessive sweep or crook.
4. Increment core shows a normal pattern of ring widths from pith to cambium, indicating no evidence of past injuries nor prolonged suppression.

Determination From Soil and Topography

The conventional method of height-age cannot be used to estimate site index if there are no trees present, or if trees are either too young or unsuitable for measurement. For example, the height-age curves developed by Hornibrook (1942) are not suitable for estimating site index because they were based on residual trees left after partial cutting, many of which were not dominants or codominants in the original stand.

Site index for granitic soils in northern Colorado and southern Wyoming can be estimated from the depth of soil to the top of the C horizon and elevation in feet (Sprackling 1972). Data came from 127 plots located on the Roosevelt, Arapaho, Medicine Bow, and Routt National Forests. The equation from which figure 12 is derived is shown below:

$$\hat{Y} = -106.64 + 62.46X_1 + 809.40X_2$$

where

Y = site index

X_1 = log of soil depth to top of C horizon, in inches

X_2 = 1000/elevation, in ft.

$$S_{\bar{y}\cdot x} = 9.00; \pm R^2 = 0.65$$

Site indexes estimated from these soil and topographic factors are strictly applicable only to the point sampled. The more variable the site, the more points must be sampled to precisely estimate site index over the area. In practice, however, site index sampled from what appear to be extremes on the ground for any given area is usually all that is needed.

Soil-topographic site indexes have not been developed for other areas in the central and southern Rocky mountains.

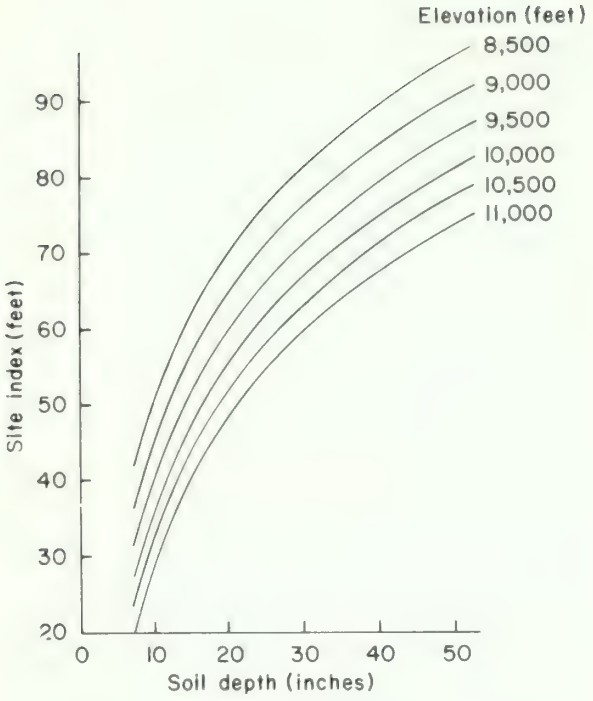

Figure 12.—Site index for Engelmann spruce on granitic soils in southern Wyoming and northern Colorado, from soil depth to the top of the C horizon and elevation (Sprackling 1972).

If we are to develop a true measure of site quality that includes potential productivity, regeneration capacity, and successional trends, the concept of "total site" that includes vegetation, soils, and landform appears to offer the best possibility of success.

GROWTH AND YIELD

Forest management in the spruce-fir type in the central Rocky Mountains is in a period of transition to more intensive management. Prediction of future yields and knowledge of individual tree growth are essential to the development of management practices for a variety of uses.

Growth of Individual Trees

Diameter growth is usually used to measure release because of its sensitivity to changes in stand density. Observations of diameter growth of residual spruce and fir left after partial or diameter-limit cutting show that individual trees respond to release, and the degree of release is related to initial diameter, tree vigor, and number of competitors (Hornibrook 1942, Roe and DeJarnette 1965, Stettler 1958). However, conventional thinning studies have not been made in spruce-fir forests in the central Rocky Mountains, partly because of the relatively few young stands and partly because spruce and fir do not grow in such dense stands as are common in lodgepole pine. A yield study[11] currently in progress in the central and southern Rocky Mountains will provide some of the data needed to determine the diameter growth of spruce and fir in relation to stand density, age, and site quality.

The height growth of individual trees is primarily important because of the relationship between site quality and height of dominant trees at index age. For tolerant species such as spruce and fir, height growth of dominant trees is unaffected over a wide range of stand density; consequently volume growth is also less affected by changes in stand density for any given site index and age. Dominant height is, therefore, a valid site index upon which to base yield prediction. The changes in the dominant height of spruce with age and site quality are shown in figure 11. At age 120 years, for example, dominant height varies from 46 to 130 ft in response to variations in site quality. Age at breast height is used as index age because the slow, variable height growth to 4.5 ft makes the use of total age meaningless.

Under stand conditions, the crowns of spruce tend to be parabolic in shape, while fir is more conical. The relationship of crown size to individual tree growth has been determined for spruce in the central Rocky Mountains (Alexander 1971). Figure 13 shows the relationship of the crown width of open-grown spruces to diameter at breast height.

New volume tables and point sampling factors have been prepared for Engelmann spruce in Colorado and Wyoming (Myers and Edminster 1972). The nineteen tables include: (1) gross volumes in total and merchantable cubic feet, (2) gross volumes in board feet, both Scribner and International 1/4 log scales, and (3) point sampling factors for merchantable cubic feet and board feet.

Volume on an area may be determined from either: (1) measurements of tree diameters and heights, (2) measurements of diameters and sufficient heights to convert the tables to local volume tables, or (3) tree counts obtained by point sampling (Myers and Edminster 1972).

[11] *Unpublished data on file with study FS-RM-1201.25, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

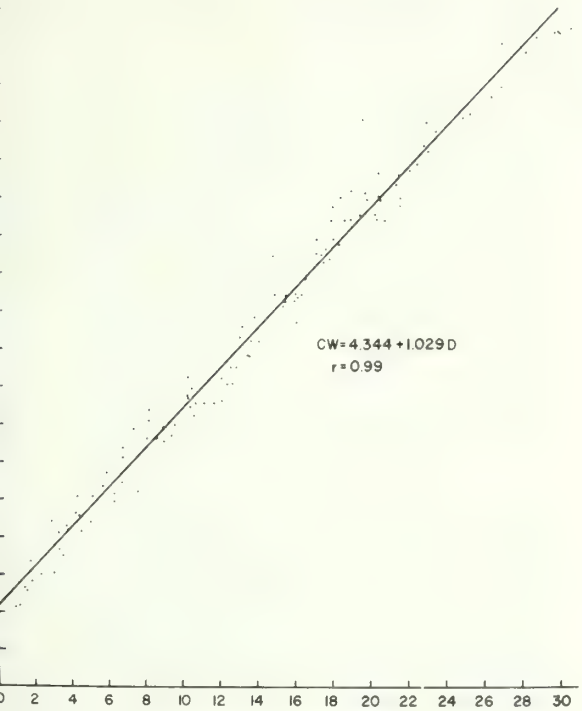

Figure 13.—Relationship of crown width to stem diameter at breast height for open-grown Engelmann spruce.

Yields Per Acre

NATURAL STANDS

With the high proportion of spruce-fir still in old-growth stands, the forest manager must largely accept what nature has provided during the period of conversion to managed stands. Growth estimates based on Forest Survey inventories, rather than detailed growth and yield studies, indicate that average annual growth over all sites in old-growth spruce-fir forests is only about 80 to 100 fbm per acre. Average volumes per acre vary from 5,000 to 15,000 fbm on poor sites to 25,000 to 40,000 fbm on better sites. Volumes as high as 80,000 to 100,000 fbm per acre have been reported (Pearson 1931, Thompson 1929, USDA-FS 1942).

MANAGED STANDS

Large areas of old-growth spruce-fir are being converted into stands that must be managed from the regeneration period to final harvest. The term managed as used here refers to control of stand density throughout the life of the stand. Yield tables for managed stands are essential to the land manager as a basis for decisions on:

1. Site quality classes that will repay the cost of thinning and other cultural treatments.
2. Levels of growing stock — including the frequency of thinning or intermediate cutting — to meet management objectives.
3. Length of rotation, cutting cycles, and allowable cut for different cutting methods, management goals, and utilization standards.
4. The place of timber management in mulitple-use management. Better decisions are possible regarding key uses when the timber potential of managed stands can be forecast.

Furthermore, yield tables that show what can be accomplished by different management practices will provide goals toward which conversion to managed stands can be directed.

The only growth-prediction tool now available for spruce-fir stands in the central Rocky Mountains was developed 30 years ago by Hornibrook (1942). However, it is for selectively cut stands, for sawtimber only, and for stand structures that are no longer management goals.

Most growth-prediction tools developed in the past have been either (1) normal yield tables, (2) empirical yield tables, or (3) experience or variable-density yield tables. Each method has deficiencies and limitations that make it unsuitable for developing growth prediction tools necessary to meet present and future needs in spruce-fir forests.

A method of yield table preparation for managed stands that avoids the limitations inherent in other methods has been developed by Myers (1971). It has been used to predict yields for managed stands of Black Hills ponderosa pine (*Pinus ponderosa* Laws.) and lodgepole pine (Myers 1966, 1967). Data are now being collected in the central Rocky Mountains and analyzed by Myers (1971) field and computer simulation procedures to develop yield tables for managed spruce-fir stands. The simulation program will generate tables derived from field data on past growth in relation to stand density, age, and site quality obtained from a large number of temporary plots in existing unmanaged but uniformly spaced spruce-fir stands. The program can produce a series of yield tables which show how projected outcomes will vary in response to changes in cultural treatments and/or variations in original stand and site conditions. With this series of yield projections, the manager can examine the probable results of his operations, make necessary changes in the management of his resources, and study the effects of these changes before money is spent on them (Myers 1971).

SILVICULTURE AND MANAGEMENT OF OLD GROWTH

Regeneration Silviculture

Spruce-fir forests can be harvested by clearcutting and shelterwood, and selection cutting, plus their modifications. The objective of each regeneration system is to harvest the timber crop and obtain adequate reproduction. The choice of cutting method depends on management objectives and environmental considerations, but stand conditions, associated vegetation, and windfall and spruce beetle susceptibility that vary from place to place on any area, impose limitations on how individual stands can be handled. Cutting to bring old-growth under management is likely to be a compromise, therefore, between what is desirable and what is possible. Management on many areas may involve a combination of several partial cutting treatments, clearcutting, and sanitation salvage cutting.

CLEARCUT AREAS

Clearcutting is a regeneration system that harvests the timber crop in one step. Since a large proportion of the spruce-fir type is in overmature sawtimber stands that offer little opportunity for future management because of their advanced age, relatively slow growth, and susceptibility to wind and insects, forest managers concerned with timber production have most often elected to convert old-growth to managed stands by clearcutting in strips, patches, and blocks. Harvesting and regeneration practices developed in the central Rocky Mountains have therefore been directed toward this objective. Much of the criticism recently leveled at clearcutting in spruce-fir has a valid basis, particularly where large openings were cut, geometric patterns were used that did not complement the landscape, unsightly logging debris was left on the ground, and areas did not regenerate. The cause of these criticisms can be eliminated if available knowledge is put into practice. From a silvicultural point of view, therefore, clearcutting is still an acceptable harvesting method in spruce-fir forests. In fact, under some conditions it is the only alternative to no cutting. Furthermore, a combination of cleared openings and high forests meets the needs of such key uses as water production and wildlife management. Consequently the following — taken chiefly from Roe et al. (1970) — will be directed at the practices needed to regenerate clearcuts. To restock these cutovers, the manager should first consider the cultivation of existing **acceptable** advanced reproduction before planning on subsequent restocking by natural or artificial means.

Management with Advanced Reproduction

Although many spruce-fir forests have an understory of advanced growth, wide variations in age, composition, quality, and quantity of advanced reproduction require careful evaluation of the potential for future management. This management potential must be determined before cutting. One course of action is followed if the advanced reproduction is to be managed, another if a manageable stand is not present, cannot be saved, or the manager chooses to destroy it and start over (Roe et al. 1970).

Prelogging Evaluation. — The initial examination must answer the following questions: (1) How much of the area is stocked with acceptable seedlings and saplings, and will that stocking insure a satisfactory replacement stand? (2) Can it be logged economically by methods that will save advanced reproduction? Is the timber volume too heavy to save advanced reproduction if it is removed in one cut? (3) How much of the area will require subsequent natural or artificial regeneration, either because advanced reproduction is not present or will be destroyed in logging?

Since any kind of cutting is likely to destroy at least half of the advanced growth, a manageable stand of advanced reproduction before cutting should contain at least 600 acceptable seedlings and saplings per acre of either spruce or fir. There are few data available on the growth response of advanced reproduction; the following criteria are therefore based largely on experience and observation. To be acceptable, reproduction must be of good form, able to make vigorous growth when released, and be free of defect or mechanical injury that cannot be outgrown. Trees over 4 inches d.b.h. may be acceptable, but they should not be included in the prelogging regeneration survey because they are more likely to be damaged or destroyed in logging or windthrown after logging. Stands or portions of stands not meeting these criteria will have to be restocked with subsequent natural or artificial regeneration (Roe et al. 1970).

Cutting and Slash Treatment to Save Advanced Regeneration. — Mature and overmature trees should be cut to release advanced reproduction and harvest merchantable volume. Seed sources need not be reserved from

cutting unless required for fill-in stocking. If it is necessary to reserve trees for esthetic purposes or maintain high forests for other uses, some form of partial cutting that will release and protect advanced growth should be considered. The size, shape, and arrangement of openings cut is not critical from a regeneration standpoint, but to be compatible with other key uses, openings should be no wider than about five to eight times tree height, irregular in shape, and blend into the landscape. Not more than one-third of any drainage or Working Circle should be cut over at any one time.

Protection of advanced reproduction begins with a well-designed logging plan (Roe et al. 1970). Logging equipment must be suited to the terrain. Skidding, movement of equipment, and other activity must be rigidly controlled. To minimize damage to advanced reproduction and disturbance to soil, skid roads must be located and marked on the ground before cutting. They should be at least 200 ft apart. Movement of skidding equipment must be confined to these skid roads to eliminate indiscriminate travel over the area. Trees should be felled into openings where possible at a herringbone angle to the skid road so as to reduce disturbance when logs are moved onto the skid road (Alexander 1957a, Roe et al. 1970). It may be necessary to deviate from a herringbone felling angle in order to drop the trees into openings. If this is the case, the logs will have to be bucked into short lengths to reduce skidding damage. Furthermore, there must be close coordination between the felling and skidding operations, because it may be necessary to fell and skid one tree before another is felled. Dead sound material and snags that are felled should be skidded out of the area to minimize the amount of slash and unmerchantable material to be disposed of after logging.

Slash treatment should then be confined to areas of heavy concentrations as required for protection from fire and insects or preservation of esthetic values (Roe et al. 1970). Slash must be treated carefully to avoid unnecessary damage to advanced reproduction — care taken in logging is wasted if advanced reproduction is destroyed in slash disposal. If trees are felled into openings as much as possible, a minimum of turning and travel with brush dozers will be needed to concentrate the slash for burning. Sufficient piles should be made so that burning is confined to the smallest area possible.

Postlogging Reevaluation. — Regardless of how much care is taken in logging and slash treatment, a certain amount of advanced reproduction will be damaged or destroyed. The area must be surveyed to: (1) Determine the extent of damage to the reproduction. At least 300 acceptable seedlings and saplings per acre must have survived to consider the area adequately stocked plus whatever trees larger than 4 inches d.b.h. survive intact (fig. 14). Areas that do not meet these standards will need fill-in

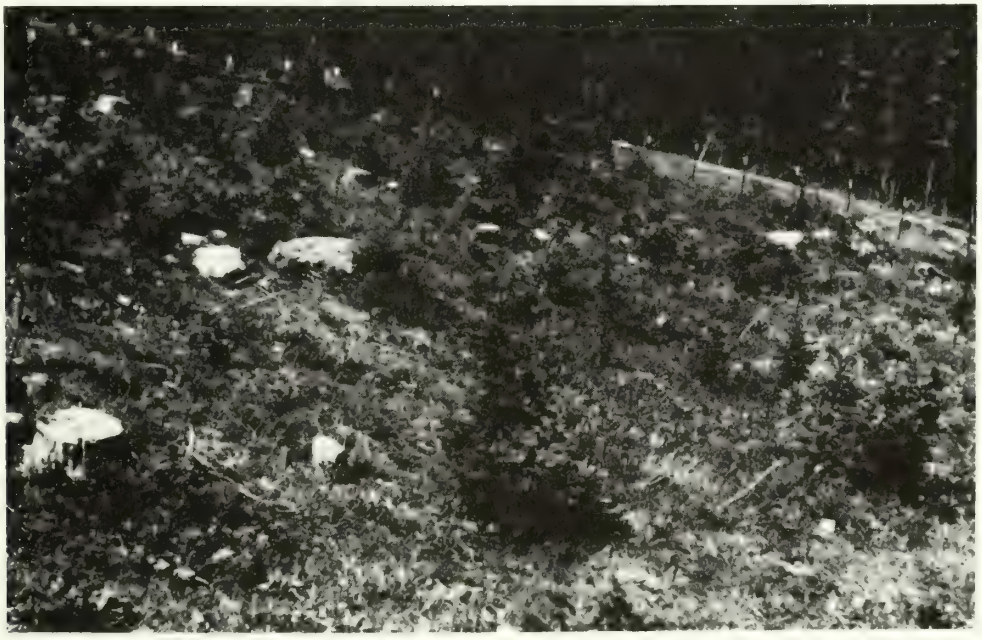

Figure 14.—Adequate stocking of advanced spruce and fir reproduction after clearcutting and slash disposal. Fraser Experimental Forest, Colorado.

or supplemental stocking. (2) Plan stand improvement — cleaning, weeding, and thinning — to release crop trees. Guidelines are available to aid in marking trees to be cut or left (Alexander 1957b).

Cutover areas should not be considered in an adequate growing condition until the crop trees are free to grow and the necessary fill-in planting or natural regeneration is complete (Roe et al. 1970).

Management for Reproduction After Cutting

If advanced reproduction is not adequate, the area must be regenerated by natural or artificial means after logging.

Cutting unit layout, logging plans, slash disposal, and seedbed treatment should be designed to (1) facilitate seed dispersal, (2) promote seedling survival and establishment, and (3) create favorable growing conditions. If natural regeneration fails, plans must then be made to use artificial regeneration (Roe et al. 1970).

Clearcutting can be by patches, blocks, or strips. Such cutting can be readily adapted to multiple use land management by judicious selection of size, shape, and arrangement of openings in combination with other high-forest cutting practices.

Size of Cutting Unit. — Requirements for seed dispersal and site preparation will influence the size of opening that will restock to natural regeneration. The best seedbed preparation is wasted if the seedbed does not receive sufficient seed; likewise, any quantity of seed is wasted if it does not fall on a receptive seedbed (Roe et al. 1970). The cutting unit must therefore be designed so that seed from the surrounding timber margin reaches all parts of the opening unless supplementary artificial regeneration is planned. Effective seeding distance and aspect determine the size of opening.

The tabulations below are guides developed for the central Rocky Mountains. They are based on 12 years of seed production and dispersal data from six areas in Colorado (Alexander 1969, Ronco 1970b, Ronco and Noble 1971) and 5 years of spruce survival data from the Fraser Experimental Forest in Colorado in a *Picea engelmannii-Vaccinium* spp. habitat type (see footnote 9). Effective seeding distance as used here is defined as the distance to which sufficient sound seed is dispersed to provide an arbitrary minimum of 1,000 first-year seedlings on (1) mineral soil seedbeds where competition from competing vegetation has been eliminated, and 50 percent overhead shade and protection from rodents provided; and (2) natural seedbeds with only protection from rodents provided. The number of first-year seedlings expected to become established on two aspects is:

Seedbed and aspect	Seedlings per 1,000 sound seeds
Shaded, mineral soil:	
North	50
South	10
Unshaded, natural:	
North	5
South	0

The estimated maximum distance that can be seeded from all sides and size of opening that can be made on two aspects based on moderate to good seed production is:

Seedbed and aspect	Maximum — Distance that can be seeded (ft)	Size opening (tree heights)
Shaded, mineral soil:		
North	450-500	5-6
South	150-200	2-2½
Unshaded, natural:		
North	50-100	1-1½
South	0	0

Based on these seeding distances, the following conclusions can be drawn:

1. Clearcutting for natural regeneration is most likely to succeed on north and east aspects, if the right combination of mineral soil and shade has been created. Even then, more than one good seed year will likely be required to obtain adequate restocking.
2. Clearcutting on south and west aspects is not likely to result in an acceptable stand of new reproduction in a reasonable period of time, even with favorable seedbed and environmental conditions, without fill-in planting to bring reproduction to the minimum acceptable standard.
3. Where larger openings than shown are cut on north and east slopes, it will be necessary to plant the area beyond effective seeding distance.
4. Where the seed source is of poor quality, plan to plant the cutovers.

Similar guides developed for Intermountain egion conditions by Roe et al. (1970) show that rger openings than indicated here can be re-ocked if the seed source contains 200 or more ² of basal area in spruce trees 10 inches d.b.h. nd larger.

Windfall. — A significant consideration in the cation of cutting unit boundaries is windfirm-ess. Not only are the trees along the margins of penings the source of seed for regeneration, ut they also provide ideal breeding grounds for pruce beetles when windthrown. The following uidelines for minimizing windfall around the erimeter of clearcut openings were developed Colorado (Alexander 1964, 1967b):

1. Protection from wind for the vulnerable leeward boundaries is most important.
2. Do not locate cutting boundaries where they will be exposed to accelerated winds funneling through saddles in ridges to the south and west of the cutover area, especially if the ridges are at high elevations. Success in reducing blowdown from that kind of exposure depends upon the ability of the forester who lays out the cutting-unit boundaries to recognize exceptionally hazardous situations.
3. Avoid locating cutting boundaries on ridges or near saddles in ridges, especially ridgetops of secondary drainages to the lee and at right angles to the main drainage when the latter is a narrowing valley with steep slopes. One cutting unit should straddle each ridgetop and extend downslope in both directions for a distance of at least 200 ft. That unit may be cut or uncut. Such an arrangement will avoid leaving a cutting boundary on the top of a ridge.
4. Lay out each unit so the maximum amount of cutting boundary is parallel to the contour or along a road where topography, soils, and stand conditions will permit.
5. Do not lay out cutting units with dangerous windcatching indentations or long, straight lines and square corners in the leeward boundary or in boundaries that are parallel to stormwinds. V- or U-shaped indentations in the boundary can funnel wind into the reserve stand. Long, straight cutting-boundary lines and square corners also deflect the wind and cause increased velocities where the deflected currents converge with others such as a windstream flowing over a crest. Irregular cutting boundaries without sharp indentations or square corners lessen the opportunity for deflection and funneling of air currents.
6. Do not locate cutting boundaries on poorly drained or shallow soils. Trees grown under these conditions are shallow rooted and susceptible to windthrow.
7. Locate cutting boundaries in stands of sound trees. Trees with decayed roots and boles or root systems that were cut or torn during road building or log skidding operations are poor windfall risks.
8. Locate cutting boundaries in immature stands when possible. Stands of young trees are usually less easily uprooted by strong winds.
9. Locate cutting boundaries in poorly stocked stands. Open-grown trees are more windfirm than trees grown in dense stands.
10. Avoid locating cutting boundaries in areas where there is evidence of old prelogging blowdowns.
11. Reduce blowdown in areas with exceptionally hazardous windfall potential by locating the vulnerable leeward boundaries where hazards are below average, or by eliminating those boundaries by progressive cutting into the wind.

Seedbed Preparation and Slash Treatment.—There are a number of things to consider when planning the treatment of spruce slash: (1) slash 8 inches in diameter or larger provides a habitat for spruce beetles; (2) it provides beneficial shade for germination and seedling establishment; (3) in heavy concentrations, it obstructs natural seedling establishment; and (4) it creates an adverse visual impact.

Burning slash in large concentrations such as windrows or piles often creates enough heat in the soil to inhibit the development of any kind of plant growth for an unknown period of time. Windrows or piles should therefore be small or narrow, and should cover a minimum proportion of the area.

Mineral soil can be exposed by mechanically scarifying the ground surface, sometimes in connection with slash disposal or by broadcast burning. To be effective, broadcast burning should accomplish certain objectives. It should consume most but not necessarily all of the duff or organic material on the ground, and it should burn hot enough to destroy some or all of the competing vegetation. On the other hand, it should not burn so hot that a deep layer of loose ashes accumulates, the mineral soil changes color, or the rocks fracture. It must leave cull logs, tops, and other large slash to provide shade and protection for soil and seedlings (Roe et al. 1970). Timing of the burn is exceedingly important. The spruce type is generally so cool and moist that times when effective broadcast burns can be achieved are limited. The key to

the time to burn is the moisture content of the duff — it must be dry enough to be consumed. If only the surface is dry, a blackened organic layer that inhibits seedling establishment will remain (Roe et al. 1970).

Careful mechanical scarification will prepare a satisfactory seedbed if it exposes mineral soil and destroys some of the competing vegetation, but leaves shade protection. At least 40 percent of the area should be left as exposed mineral soil. It may be necessary, however, to rearrange some of the residual slash to provide adequate shade. Tractors equipped with brush blades should be used. A complete cleanup job is neither necessary nor desirable. There is a double advantage in not cleaning up too thoroughly: First, residual tops and slash shade the seedbed; second, residual organic material reduces soil erosion. Cut green spruce material over 8 inches in diameter should be removed or treated to prevent the buildup of spruce beetle populations, but true fir material may be left. On highly erodible soils, the duff layer should be removed along the contour, preferably in strips the width of the dozer blade, with untouched strips intervening. Some of the larger debris may then be pushed back on the scarified strips for protection from erosion, and the dozer walked over it at right angles to the strips to break it down (Roe et al. 1970).

Management for Artificial Regeneration

Planting. — Guidelines for planting spruce in the central and southern Rocky Mountains have been prepared by Ronco (1972). His recommendations are summarized here unless otherwise indicated.

1. *Need and Timing.* — Good sites should be planted **immediately** after logging where there is not a manageable stand of advanced reproduction, and where local experience has shown that natural regeneration is likely to take a long time. Areas logged and prepared for natural regeneration that fail to restock in 3 to 5 years should be planted before invasion by other vegetation has completely occupied the site. Experience has shown that a minimum goal should be about 300 well-established spruce seedlings in addition to whatever other species may have become established (Roe et al. 1970).

   Planting cutover areas has several advantages. By growing stock in nurseries, many of the vagaries of the natural regeneration system are avoided, such as unpredictable seed years, irregular seed dissemination, and high rates of early seedling mortality. Planting permits better control of stand density, tree distribution, and species and genetic composition of the stand. Planting, unlike natural regeneration, does not impose a restriction on size of cutting units, and it removes the necessity of reserving merchantable trees for seed. Furthermore, successful planting may shorten the regeneration period (Roe et al. 1970).

   There are, however, some disadvantages in planting. Field planting requires close coordination between cutting plans and the availability of planting stock. Delay in planting after logging may increase the costs of site preparation. Costs of surviving seedlings are frequently higher than those of natural regeneration. Close supervison is needed to assure planting of only large, vigorous stock, proper storage and transportation, proper handling of stock from the nursery until planted, and proper planting techniques. Furthermore, planting spruce requires just as much site preparation as natural seeding. Many planting failures in the Rocky Mountains can be traced to one or more of the disadvantages mentioned above (Roe et al. 1970).

2. *Site Preparation.* — Site preparation for spruce plantations probably requires more consideration than for most other species because of the complex relationship between the environment and seedling requirements. For example, warmer soils and increased moisture availability accompanying complete vegetation removal would benefit seedlings, but because of their sensitivity, seedlings would be more prone to severe injury from intense light and frost. Therefore, in the absence of logs or stumps, live vegetation such as willows, Potentilla, fireweed, Vaccinium, or other species of similar growth habit may be desirable as protective cover even though it competes with seedlings.

   Hand scalping will probably be adequate for most planting operations. Hand-scalped spots should not be smaller than 18 to 24 inches square. Above-ground parts of plants are totally removed, but lateral roots from vegetation surrounding the scalp usually remain active. Thus the zone of soil released from the competitive effects of vegetation tapers rapidly below the ground surface.

   Heavy concentrations of slash should be treated to reduce fire and insect hazards and adverse visual impacts, but slash disposal and seedbed preparation with heavy machinery should be minimized. Removing vegetative competition or treating slash can adversely affect plantation establishment by

destroying microsites that afford protection for planted seedlings. Machines could be used, however, to obtain better distribution of favorable microsites over the plantation by rearranging logs. Exposure of mineral soil during such operations would also create favorable seedbeds, which might result in supplemental stocking from natural regeneration.

In areas where hand scalping is unsatisfactory because of dense sod-forming grasses and sedges or a heavy cover of herbaceous species such as Mertensia, vegetation may be controlled by such machine methods as disking, furrowing, mounding, ridging (berms resulting from plowing), and bulldozing. Where competing vegetation consists of relatively tall brush species that form dense cover, complete removal or cleared strips of bulldozer-blade widths may be desirable. Machine scalping with disks or plows (furrowing or ridging) should leave vegetation-free areas 1.5 to 2 ft wide.

Broadcast burning can be used on areas where there is no advanced reproduction or residual stand. Logs not consumed in the fire will provide shade for planted seedlings (Roe et al. 1970).

. *Planting Stock.* — Plant only stock that meets the following specifications: (1) Tops should be no shorter than 3 to 4 inches; they should be well developed with not less than two or three branches. (2) Roots should not be shorter than 5 to 6 inches; they should be compact, fibrous, and well developed with several lateral roots. (3) Tops and roots should have a low shoot/root ratio.

. *Planting Season.* — Plant spruce in the spring after snowmelt. Planting usually should be completed before June 25, but may be extended to July 10 if moisture does not become depleted or temperatures unseasonably high. Temporarily suspend planting during the regular season when temperatures are unseasonably warm, especially on clear days when the wind is blowing.

. *Storage.* — Nearly all planting in the central and southern Rocky Mountains requires that seedlings be lifted while they are still dormant and stored at the nursery until planting sites are free of snow. Because of the incidence of mold and depletion of food reserves, spruce should not be held in storage longer than 3 months. Seedlings must be treated as dormant plants during transit to planting sites. If refrigerated transport is not available, cover the bundles or bags with canvas to maintain temperatures between 34° to 40° F. Storage problems are more severe in the field because limited facilities on the planting site make temperature control difficult. Well-insulated storage sheds that can be cooled by ice or snow can be used in the absence of mechanical refrigeration. If such storage is not available, cool, moist cellars or even snowbanks can be used. Seedlings can be held in storage locally up to 7 days if temperatures can be maintained below 40° F.; otherwise limit local storage to 3 days. When transferring seedlings from bundles or bags to planting containers, handle the seedlings carefully to prevent root breakage and do not expose roots to sun or wind.

6. *Spot Selection.* — Plant seedlings with roots in moist soil and only on those spots where seedlings are protected by stumps, logs, slash, or open cover of live vegetation, and only on the north and east side of protective cover (fig. 15). Avoid planting in depres-

Figure 15.—Good spot selection. Engelmann spruce seedling planted on the east side of a log where shade is fully utilized.

sions, frost pockets, on small mounds, in areas with an extensive cover of sod-forming vegetation, where advanced regeneration shows evidence of snow mold, and where skidding and slash disposal have buried trash in the soil.

7. *Planting Method.* — Use the hole method; dig holes with mattock hand tools or power augers. If power augers are used, do not dig holes too far in advance of planting.
8. *Plantation Protection.* — Protect new plantings from trampling by livestock until seedlings are at least 3 ft high. They may require fencing or other adjustments in grazing allotments. New plantings should also be protected from rodents. Sample the rodent populations on the areas scheduled to be planted. If populations are large, provide controls until seedlings become established.

9. *Records.* — Adequate data from detailed records are needed to (1) correct deficiencies causing failure, and (2) recognize good practices leading to successful plantations. Decisions affecting regeneration practices can then be based on quantitative information rather than conjecture. Follow the recommendations suggested by Ronco (1972).

Seeding. — Until reliable techniques have been worked out for the central and southern Rocky Mountains, direct seeding of spruce is not recommended as an operational regeneration practice.

PARTIAL CUT AREAS

Partial cutting here includes both shelterwood and selection cuts and their modifications. They are regeneration systems that harvest the timber on an area in more than one step. From a silvicultural point of view these are acceptable harvesting methods in old-growth spruce-fir. They are, in fact, the only options open to the manager where (1) multiple use considerations preclude clearcutting, (2) combinations of small cleared openings and high forests are required to meet the needs of various uses, or (3) areas are difficult to regenerate after clearcutting. However, windfall, insects, and stand conditions impose limitations on how stands can be handled. A **careful appraisal** of the capabilities and limitations of each stand is necessary to determine cutting practices. Furthermore, partial cutting requires **careful marking** of individual trees or groups of trees to be removed, and **close supervision** of logging.

A classification based on stand characteristics is needed to (1)identify the kinds of stands that can be partially cut, those that must be clearcut and started new, and those that should be uncut; and (2) develop partial cutting practices for different management objectives. Until such a classification is available, the following recommendations for partial cutting practices are keyed to **broad stand descriptions** based largely on experience, windfall risk situations, and insect problems (Alexander 1973). Practices needed to obtain natural reproduction are also discussed.

Single-Storied Stands[12]

Description. —

1. Stands may appear to be even-aged (fig. 16), but usually contain more than one age class. In some instances, the canopy may not appear to be of a uniform height because of changes in topography, stand density, or stocking.
2. Codominant trees form the general level of the overstory canopy. Dominants may be 5 to

[12]*Reproduction less than 4.5 ft tall is not considered a stand story in these descriptions.*

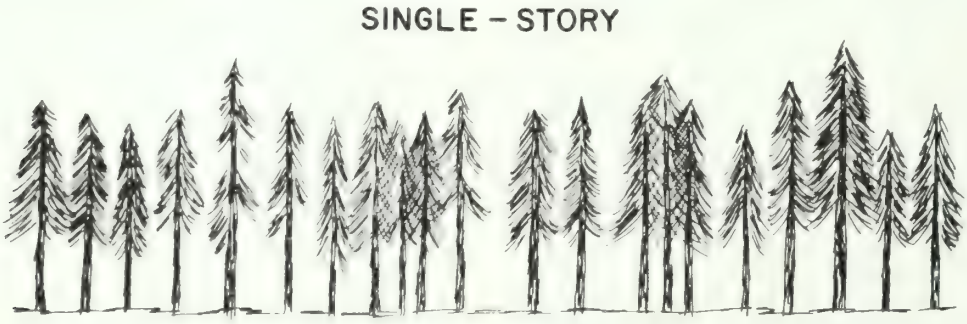

Figure 16.—A single-storied spruce-fir stand.

10 ft taller, and occasionally predominants may reach 15 to 20 ft above the general canopy level. Taller intermediates extend into the general canopy; shorter intermediates are below the general canopy level but do not form a second story.

3. The range in diameters and crown length of dominants and codominants is small.
4. There are few coarse-limbed trees in the stand; if two-aged or more, younger trees usually have finer branches and may not have diameters equal to the older trees.
5. Trees are more often uniformly spaced than clumpy.
6. A manageable stand of advanced reproduction usually is not present.[13]
7. If lodgepole is present in the overstory it is not a major stand component. Lodgepole pine reproduction is absent or sparse.

Recommended Cutting Treatments. — These stands are usually the least windfirm because trees have developed together over a long period of time and mutually protect each other from the wind.

1. **If the windfall risk is below average, and the trees are uniformly spaced —**

   a. The first cut should be light, removing about 30 percent of the basal area of the stand on an individual tree basis.[14] This type of cutting resembles the first or **preparatory cut** of a three-step shelterwood. Since all overstory trees are about equally susceptible to windthrow, the general level of the canopy should be maintained by removing some trees from each overstory crown class. Those trees with known indicators of defect should be removed first, but avoid creating openings in the canopy with a diameter larger than one tree height by distributing the cut over the entire area. Furthermore, do not remove dominant trees in the interior of the stand that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut. In these and all other stands described where natural openings one to several acres occur, leave the trees around the perimeter for a distance of about one tree height until the final entry. These trees have been exposed to the wind and are usually windfirm, and protect the trees in the interior of the stand.

   b. The second entry into the stand should not be made for at least 5 to 10 years after the first cut in order to determine if the residual stand is windfirm. This cut should also remove about 30 percent of the original basal area on an individual tree basis. It simulates the second or **seed cut** of a three-step shelterwood. The largest and most vigorous dominants and codominants should be reserved as a seed source, but avoid cutting openings in the canopy larger than one tree height in diameter by distributing the cut over the entire area, even if it means leaving trees with poor seed production potential.

   c. The last entry is the **final harvest** and should remove all of the remaining original overstory. It should not be made until a manageable stand of reproduction has become established, but the cut should not be delayed beyond this point if timber production is one of the primary concerns because the overwood hampers the later growth of seedlings.

   d. The manager also has the option of removing less than 30 percent of the basal area at any entry and making more entries, but they cannot be made more often than every 5 to 10 years. This will spread the cut out and maintain a continuous forest cover for a longer period of time.

2. **If the windfall risk is below average, and the trees are clumpy —**

   a. The first cut should be a modified **group selection** that removes about 30 percent of the basal area. Harvesting timber in groups will take advantage of the natural arrangement of trees in clumps. Group openings should be kept small — not more than one to two tree heights in diameter — and not more than one-third of the area should be cut over (fig. 17). However, all trees in a clump should be either cut or left since they mutually support each other, and removing only part of a clump is likely to result in windthrow of the remaining trees.

   b. The second entry into the stand should not be made until the first group of openings has regenerated. This cut can also remove about 30 percent of the original

[13] *Since any kind of cutting may destroy as much as half of the advanced reproduction, even with careful logging, at least 600 spruce or fir seedlings and saplings per acre, of good form and vigor and free of defects, must be present to be considered a manageable stand.*

[14] *As a practical matter, small saplings that do not represent significant competition to the remainder of the stand may be excluded from the computation of basal area.*

Figure 17.—Group-selection cutting in spruce-fir. One-third of the area was cut in openings about one tree height in diameter. Fraser Experimental Forest, Colorado.

basal area without cutting over more than an additional one-third of the area. Openings should be no closer than about one to two tree heights to the openings created by the previous cut.

c. The final entry should remove the remaining groups of merchantable trees. The timing of this cut depends upon how the manager elects to regenerate the new openings. If he chooses to use natural regeneration the final harvest must be delayed until the regeneration in the openings cut earlier are large enough to provide a seed source.

d. The manager may choose to remove less than 30 percent of the basal area and cut over less than one-third of the area at any one time. This will require more entries, but each new cut should not be made until the openings cut the previous entry have regenerated. Furthermore, the last groups cannot be cut until there is either a seed source or the manager elects to plant these openings.

3. **If the windfall risk is above average, and the trees are uniformly spaced —**

a. The first cut should be restricted to a very light **preparatory** cutting that removes about 10 percent of the basal area on an individual tree basis. The objective is to open up the stand, but at the same time minimize the windfall risk to the remaining trees. This type of cutting resembles a **sanitation cut** in that the poorest risk trees — those of low vigor and with known indicators of defect — and predominants should be removed, but it is important that the general level of the overstory canopy be maintained intact. Provision should be made to salvage windfalls after spruce beetle flight at the end of July.

b. The second entry can be made in about 10 years after the first cut. This entry should remove about 15 to 20 percent of the original basal area on an individual tree basis. Any windfall salvaged after the first cut should be included in the computation of the basal area to be removed. The objective of this **preparatory cut** is to continue to open up the stand gradually while preparing the stand for the seed cut. Most of the trees marked for removal should come from the intermediates and small codominants, but maintain the general level of the canopy intact.

c. It will require another 5 to 10 years to determine if the stand is windfirm enough to make another entry. This will be the **seed cut,** and should remove about

20 to 25 percent of the original basal area including any windfalls salvaged since the last cutting. The largest and most vigorous dominants and codominants should be reserved as a seed source, but it is more important to distribute the cut over the entire area.

d. The last entry is the **final harvest** to remove the remaining original overstory. It cannot be made until a manageable stand of reproduction has been established. About 50 percent of the original basal area will be removed in this cut, and if this is more than 10,000 fbm per acre, it is probably too heavy to be removed in one harvest without undue damage to the reproduction. The manager must therefore plan on a two-step final harvest. The second step can begin as soon as the skidding is finished in the first step, providing that a manageable stand of reproduction still exists.

If the windfall risk is above average and the trees are clumpy —

a. The first cut should be light, removing about 15 to 20 percent of the basal area in a modified **group selection**. Group openings should be no larger than one tree height in diameter, and not more than one-fifth of the area should be cut over at any one time. All trees in a clump should be cut or left. In stands with small natural openings — about one tree height in diameter — the openings can be enlarged one tree height by removing clumps of trees to the windward.

b. Four additional entries into the stand can be made at periodic intervals, but each new entry should not be made until the openings cut the previous entry have regenerated. The last groups to be removed should be retained until the original group openings are large enough to provide a seed source. About 20 percent of the basal area should be removed over about one-fifth of the area at each entry. Group openings should be no larger than one tree height in diameter.

5. **If the windfall hazard is very high —**

The choice is limited to removing all the trees or leaving the area uncut. Cleared openings should not be larger than regeneration requirements dictate, and they should be interspersed with uncut areas of at least equal size. Not more than one-third of the total area in this wind risk situation should be cut over at one time.

Two-Storied Stands

Description. —

1. Stands may appear to be two-aged (fig. 18), but usually contain more than two age classes.
2. The top story (dominants, codominants, and intermediates) is usually spruce; resembles a single-storied stand.
3. The second story is often fir, and the trees are younger and smaller in diameter than the overstory. It may consist of small saw logs, poles, or large saplings, but is always below the top story and clearly distinguishable from the overstory. Trees in the second story are overtopped, but not suppressed.
4. There may be a manageable stand of advanced reproduction.
5. Arrangement of individual trees varies from uniform to clumpy.
6. If lodgepole pine is present in the stand it is usually a scattered component of the overstory. Lodgepole pine reproduction is absent or sparse.

Figure 18.—A two-storied spruce-fir stand.

Recommended Cutting Treatments. — Same as for three-storied stands.

Three-Storied Stands

Description. —

1. Stand may appear to be three-aged (fig. 19), but usually contains more than three age classes. Occasionally two-aged, but is never all-aged.
2. If the stand is three-aged or more, the top story is usually predominantly spruce and resembles a single-storied stand except that there are fewer trees. The second and third stories are usually younger and smaller diameter trees (small saw logs, poles, and large saplings) that are usually fir. In a typical stand, the second story will be 10 to 30 ft below the top story and consist of small saw logs or large poles. Third story will be 10 to 30 ft below the second story and consist of small poles or large saplings. Although the second and third stories are overtopped, the trees are usually not suppressed.
3. If two-aged, the first two stories are old-growth with spruce in the top story and fir in the second story. The third story will be younger trees, largely fir, of smaller diameter.
4. Frequently contains a manageable stand of advanced reproduction.
5. More often clumpy than are single- or two-storied stands.
6. If lodgepole pine is present, it is usually a scattered component of the top story, but may occur in the second story. Lodgepole pine reproduction is usually absent or sparse.

Recommended Cutting Treatments (Two- and Three-Storied Stands). —Trees in the overstory are usually more windfirm than those in single-storied stands. The second and third stories are likely to be less windfirm than the top story.

1. **If the windfall risk is below average, and the trees are uniformly spaced —**

   a. The first cut can remove about 40 percent of the basal area where there is not a manageable stand of advanced reproduction. This type of cutting is heavy enough to resemble the first step or **seed cut** of a two-cut shelterwood, but the marking follows the rules for individual tree selection — mature trees are removed from each story. Since the overstory is likely to be more windfirm, selected dominants and codominants of good vigor and free of defect should be left. These trees are also the most desirable seed source. Avoid cutting holes in the canopy larger than one tree height in diameter by distributing the cut over the entire area. Furthermore, do not remove dominant trees from the interior of the stand that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut.

   b. The second entry should be the **final harvest** to remove the remaining original stand and release the reproduction. It cannot be made until the new stand of reproduction is established. If the residual volume is greater than about 10,000 fbm per acre, the **final harvest** should be made in two steps to avoid undue damage to newly established reproduction. The second step can begin as soon as the skidding is finished in the first step, providing that a manageable stand of reproduction still exists.

   c. If there is a manageable stand of advanced reproduction, the first cut can be an **overstory removal** if the volume is not too heavy. Otherwise, the first cut can remove 40 percent of the basal area on an individual tree basis as long as the more windfirm dominants and codominants are left. The timing of the second cut is not critical from a regeneration standpoint,

Figure 19.—A three-storied spruce-fir stand.

providing a manageable stand of reproduction still exists after the first cut.

d. The manager has other options to choose from. He may elect to cut less than the recommended basal area, make more entries, and spread the cut out over a longer period of time by delaying the final harvest until the new stand is tall enough to create a continuous high forest. He may also elect to convert these stands to an uneven-aged structure by making a series of light cuts — 10 to 20 percent of the basal area — at frequent intervals — 10 to 20 years. Ultimately the stand will contain a series of age classes.

2. **If the windfall risk is below average, and the trees are clumpy —**

a. The first cut should remove about 40 percent of the basal area in a modified **group selection** cutting. The group openings can be larger (two to three times tree height) than for single-storied stands, but the area cut over should be not more than one-third of the total. Furthermore, the group openings should be irregular in shape, but without dangerous windcatching indentations in the edges. All trees in a clump should either be cut or left.

b. Two additional entries can be made. They should each remove about 30 percent of the original basal area in group openings up to two to three times tree height, but not more than one-third of the area should be cut over at any one time. If there is not a manageable stand of advanced reproduction, the manager must wait until the first group of openings is regenerated before cutting the second series. Furthermore, he must either delay the cutting of the final groups until there is a seed source or plan on planting these openings. If there is a manageable stand of advanced reproduction, the timing between cuts is not critical from a regeneration standpoint.

c. The manager has the option of removing less than the recommended basal area and cutting less than the recommended area at any one time. This will require more entries and spread the cut out over a longer period of time.

3. **If the windfall risk is above average, and the trees are uniformly spaced —**

a. The first cut should be a light **preparatory** cutting that removes not more than 20 percent of the basal area, on an individual tree basis, where there is not a manageable stand of advanced reproduction. Predominants, intermediates with long dense crowns, and trees with known indicators of defect should be removed first, but maintain the general level of the canopy. The objective of this cut is to open up the stand, but at the same time minimizing the windfall risk to remaining trees. Provision should be made to salvage windfalls after spruce beetle flight.

b. The second entry into the stand should not be made in less than 10 years. This cut should remove about 30 percent of the original basal area, including the salvage of any windfalls that occur between the first and second cuts. The second entry is the **seed cut,** therefore the best dominants and codominants should be reserved as a seed source, but it is important that the cut be distributed over the entire area.

c. The next entry is the **final harvest** to remove the remaining merchantable volume and release the new reproduction after it has become established. However, if the residual stand has too heavy a volume, the final harvest should be made in two steps.

d. If these stands contain a manageable stand of reproduction and the volume per acre is not too heavy, the first cut can be an **overwood removal.** If the volume is too heavy for a one-step removal, the manager should follow the recommendations above because the wind hazard is too great to permit a two-step removal in a stand that has not been previously opened up.

4. **If the windfall risk is above average, and the trees are clumpy —**

a. The first cut should be a modified **group selection** that removes about 25 percent of the basal area. Group openings should be kept small — not more than one to two tree heights in diameter — and not more than one-fourth of the area should be cut over at any one time. All trees in a clump should either be cut or left. Small natural openings can be enlarged one to two tree heights by removing trees in clumps to the windward of the opening.

b. Three additional entries should be made. If there is not a manageable stand of advanced reproduction, about 25 percent of the original basal area should be removed on about one-fourth of the area in each entry. The interval between cuts will depend upon the time required to regener-

ate each series of openings. The manager must either delay the removal of the final groups until a seed source is available or plant the openings. If there is a manageable stand of advanced reproduction, the timing between cuts is not critical from a regeneration standpoint.

5. **If the windfall hazards are very high —**

   The choice is usually limited to removing all the trees or leaving the area uncut. Cleared openings should not be larger than regeneration requirements dictate, and should be interspersed with uncut areas. Not more than one-third of the total area in this windfall risk situation should be cut over at any one time.

Multi-Storied Stands

Description. —

1. Stands are generally uneven-aged (fig. 20) with a wide range in diameters.
2. If the stand developed from a relatively few individuals, overstory trees are coarse limbed and fill-in trees are finer limbed. The overstory trees may be relatively vigorous.
3. If the stand developed from the deterioration of a single- or two-storied stand, the overstory may be no limbier than the fill-in trees. Much of the vigorous growing stock is below saw log size.
4. There is almost always a manageable stand of reproduction as a ground story.
5. The fill-in trees may be clumpy, but usually the overstory trees are uniformly spaced.
6. Lodgepole pine may occur as a scattered component of the stand, usually in the overstory, but it may also occur in all stories including reproduction.

Recommended Cutting Treatments. — These are usually the most windfirm stands, even where they have developed from the deterioration of single- and two-storied stands, because by the time they have reached their present condition the remaining overstory trees are usually windfirm.

1. **If the windfall risk is below average —**

   There is considerable flexibility in harvesting these stands. All size classes can be cut, with emphasis on either the largest or smallest trees in the stand. For example, the first cut can range from removal of all large trees in the overstory to release the younger growing stock, to a thinning from below to improve the spacing of the larger trees. If the manager elects to make an overwood removal and the volume is too heavy, it should be harvested in two steps. Thereafter, cutting can be directed toward either even- or uneven-aged management, with entries made as often as growth and regeneration needs dictate.

2. **If the windfall risk is above average or very high —**

   The safest first cut is an overwood removal with a thinning from below to obtain a widely spaced, open-grown stand that will develop windfirmness. Thereafter, cutting can be directed toward either even- or uneven-aged management.

Modifications to Cutting Treatments Imposed by Spruce Beetles

1. If spruce beetles are present in the stand at an endemic level, or in adjacent stands in sufficient numbers to make successful attacks, and:

Figure 20.—A multi-storied spruce-fir stand.

a. Less than the recommended percentage of basal area to be removed is in susceptible trees, any attacked and all susceptible trees should be removed in the first cut. This will include most of the larger spruce trees and is a calculated risk, especially in above-average wind risk situations. Furthermore, the percentage of fir in the stand will increase. Provision should be made to salvage attacked trees. The remaining cuts should be scheduled in accordance with windfall risk, insect susceptibility, and regeneration needs.
b. More than the recommended percentage of basal area to be removed is in susceptible trees, the manager has three options: (1) remove all the susceptible trees, (2) remove the recommended basal area in attacked and susceptible trees and accept the risk of future losses, or (3) leave the stand uncut. If the stand is partially cut or left uncut, surviving spruce would probably make up at least half of the residual basal area, but most of the merchantable spruce would be small-diameter trees.

If the stand is sustaining an infestation that is building up and the manager chooses to either partially cut or leave the stand uncut because clearcutting is unacceptable, he must accept the risk of an outbreak that will destroy most of the merchantable spruce in the stand and spread to adjacent stands.

utting to Save the Residual

Before any cutting begins, the manager must etermine whether he has an acceptable stand advanced reproduction and if he is going to anage it. Furthermore, he must reevaluate the and after the final harvest and slash disposal determine the need for supplemental stock-g. The same criteria used to evaluate ad-anced reproduction on clearcut areas apply ere.

In partial cutting, protection of the residual om logging damage is of primary concern. he residual includes merchantable trees left ter shelterwood cutting, and advanced repro-uction in both shelterwood and group selection utting where an acceptable stand is to be man-ged. Protection begins with a well-designed gging plan at the time of the first cut. To inimize damage, skidroads must be laid ut — about 200 ft apart depending on the pography — and marked on the ground. These idroads should be kept narrow, and located so at they can be used to move logs out of the oods at each cut. Close supervision of logging ill be required to restrict travel of skidding and other logging equipment to the skidroads. In shelterwood cuttings, trees should be felled into openings as much as possible using a herringbone pattern that will permit logs to be pulled onto the skidroads with a minimum of disturbance. It may be necessary to deviate from the herringbone felling angle in order to drop trees into openings. If this is the case, the logs will have to be bucked into short lengths to reduce skidding damage. Trees damaged in felling and skidding should not be removed if they are still windfirm. In group-selection cutting, the felling pattern should be similar where there is a manageable stand of advanced reproduction. Otherwise all trees should be felled into the openings. Both shelterwood and group-selection cuttings require close coordination between felling and skidding because it may be necessary to fell and skid one tree before another tree is felled.

Slash Disposal and Seedbed Preparation

Some slash disposal will probably be needed after each cut, but it should be confined to concentrations and that needed to reduce visual impact because most equipment now available for slash disposal is not readily adaptable to working in shelterwood cuttings. Furthermore, burning of slash will cause additional damage to the residual. Skid out as much of the down sound dead and green cull material as possible for disposal at the landings or at the mill. Some hand piling or scattering may be needed where slash disposal equipment cannot be used. In group-selection cutting, if there is not a manageable stand of advanced reproduction, dozers equipped with bush blades can be used to concentrate slash for burning in the openings. Piles should be kept small to reduce the amount of heat generated. Leave some of the larger pieces of slash and other debris in place to provide shade for new seedlings. Cut green spruce material larger than 8 inches in diameter should be removed to reduce the buildup of spruce beetle populations.

On areas to be regenerated by new reproduction, a partial overstory canopy or trees standing around the margins of small openings provide two of the basic elements necessary for regeneration success — a seed source within effective seeding distance, and an environment compatible with germination, initial survival, and seedling establishment. The manager must make sure that the third element — a suitable seedbed — is provided after the seed cut where shelterwood cutting is used, and after each cut where group selection is used. If at least 40 percent of the available ground surface is not ex-

posed mineral soil after logging and slash disposal, additional seedbed preparation is needed. Until special equipment is developed, the same problem exists as with slash disposal. The equipment available today is too large to work well around standing trees. Smaller machines equipped with suitable attachments will have to be used, but they must be closely supervised to minimize damage to the residual.

Multiple-Use Silviculture

In addition to being the most productive timber type in the central Rocky Mountains, spruce-fir forests are also the highest water yielding, and are valuable wildlife, recreation, and scenic areas. Because of increasing demands on forest lands from a rapidly expanding population and the limited resource available, management must consider all key land uses. The kinds of stands that appear desirable for increased water yields, preservation of the forest landscape, maintenance of scenic values, and improvement of wildlife habitat have been suggested in a general way by both research and observation.

WATER

Water yield studies have indicated that the increase in snow depth in openings cut in spruce-fir forests is not additional snow but a change in deposition pattern (Hoover and Leaf 1967).Snow blows off adjacent standing trees and settles in the openings. The increased snow in the openings means that more water is available for streamflow. Research and experience suggest that a round or patch-shaped opening with a diameter about five to eight times the height of surrounding trees is the most effective for trapping snow (Hoover 1969). In larger openings, wind dips to the ground and scours and blows snow out of the opening. About one-third of the forest area should be in openings, which would be periodically recut when tree height reaches one-half the height of surrounding trees. The remaining two-thirds of the area would be retained as continuous high forest; trees would be periodically harvested on an individual-tree basis. Ultimately the reserve stand would approach an all-aged structure with the overstory canopy remaining at about the same height, although the original overstory could not be maintained indefinitely.

An alternative would be to make a light cut distributed over the entire watershed, removing about 20 to 30 percent of the basal area on an individual-tree basis or in small groups. The objective would be to open up the stand enough to develop windfirmness, and salvage low-vigor and poor-risk trees. Openings five to eight times tree height can then be cut on about one-third of the area. The remaining two-thirds of the area would be retained as permanent high forest, with trees periodically removed on an individual-tree basis or in small groups.

Another alternative that would integrate water and timber production would be to harvest all of the old-growth in a cutting block in a series of cuts spread over a period of 120 to 160 years. Each cutting block would contain at least 300 acres, subdivided into round or patch-shaped units approximately 2 acres in size or four to five times (in diameter) the height of a general canopy level. At periodic intervals, some of these units, distributed over the cutting block, would be harvested and the openings regenerated. The interval between cuttings could vary from as often as every 10 years to as infrequently as every 30 to 40 years. The percentage of units cut at each interval would be determined by Cutting cycle/Rotation age $\times$ 100. At the end of one rotation, each cutting block would be composed of groups of trees in several age classes ranging from reproduction to trees ready for harvest. The tallest trees would be somewhat shorter than the original overstory, but any adverse effect on snow deposition should be minimized by keeping the openings small and widely spaced.

WILDLIFE

Big-game use of spruce-fir forest lands can be improved by certain timber cutting practices, as shown in two recently completed studies. Openings of less than 20 acres cut in the canopy of spruce-fir forests in Arizona were heavily used by deer and elk, but use decreased considerably in larger openings (Reynolds 1966). Openings created by harvesting were preferred to natural openings because the vegetation that initially comes in on cutovers is more palatable to deer and elk. Reynolds suggested that openings be maintained by cleaning up the logging slash and debris, removing new tree reproduction, and seeding the area to forage species palatable to big-game. However, since natural succession on the cutover areas is likely to replace the more palatable species eventually, a more desirable alternative would be to cut new openings periodically while allowing the older cuttings to regenerate. That would provide a constant source of palatable forage and the edge effect desired, while creating an all-aged forest by even-aged groups. The openings created should be widely spaced, with

the stand between openings maintained as high forest.

On the Fraser Experimental Forest in Colorado, deer use in spruce-fir forests was greater and forage more abundant on cleared openings than in the uncut forest. Clearcut openings 3 chains wide were used more than wider or narrower strips (Wallmo 1969, Wallmo et al. 1972). While no recommendations were made as to optimum size or arrangement of openings, the Fraser study suggests that they be kept small and interspersed with standing trees that could be periodically harvested on an individual-tree basis.

One alternative that would integrate wildlife habitat improvement with timber production would be to cut about one-sixth of a cutting block every 20 years in openings about four to five times tree height. Each Working Circle would be subdivided into a number of cutting blocks (of at least 300 acres) so that not all periodic cuts would be made in a single year on a Working Circle. Such periodic cutting would provide a good combination of numbers and species of palatable forage plants and the edge effect desired, while creating a several-aged forest of even-aged groups.

Wildlife other than big-game is also influenced by the way forests are handled. For example, with the curtailment of wildfires, some reduction in stand density by logging is probably necessary to create or maintain drumming grounds for male blue grouse (*Dendragapus obscurus* Say). Partial cutting that opens up the canopy enough to allow tree regeneration to establish in scattered thickets appears to provide the most desirable habitat. Cutting small, irregularly shaped openings (up to 10 acres) in the canopy may also be beneficial to blue grouse, if thickets of new reproduction become established in the cleared openings (Martinka 1972).

RECREATION AND ESTHETICS

Permanent forest cover at least in part is preferred in recreation areas, travel influence zones, and scenic view areas. Since old-growth spruce-fir forests will not maintain themselves in an esthetically pleasing or sound condition indefinitely, some form of partial cutting would maintain forest cover while at the same time replacing the old with a new stand. However, the visual impact of logging operations — haul roads, damage to residual trees, and slash and debris — must be minimized. In situations where there is no alternative to clearcutting, and the environmental impact of clearcutting is unacceptable, there is no choice but to leave the stands uncut.

To reduce the sudden and severe visual impact on the landscape viewer, openings cut in stands for timber and water production, wildlife habitat improvement, and recreation (ski runs) should be a repetition of natural shapes, visually tied together to create a balanced, unified pattern that will complement the natural landscape (Barnes 1971). This is especially important for those openings in the middle and background that can be seen from distant views. The foreground should be maintained in high forest under some partial cutting system.

Silvicultural practices must be developed that will incorporate the maintenance of scenic values and provide the combination of continuous high forest and cleared openings necessary to integrate all land uses. This development will include: (1) classifying existing stands into categories of similar stand characteristics as a means of identifying management potentials, and (2) testing silvicultural systems and cultural practices in stands of different characteristics for a variety of management objectives.

THE LODGEPOLE PINE TYPE

CHARACTERISTICS OF THE TYPE

The lodgepole pine type is generally pictured as an even-aged, single-storied, overly dense forest, varying in age from place to place but uniform in age within any given stand. This is true only where favorable fire, seed, and climatic conditions once combined to produce a large number of seedlings at one time (Lexen 1949). Elsewhere, lodgepole pine grows on a wide range of sites with a great diversity of stand conditions. It can occur as two-aged, single- or two-storied stands; three-aged, two- or three-storied stands; and even-aged to broad-aged multi-storied stands (Tackle 1954a, 1955). Multi-storied stands, and to a lesser extent, two- and three-storied stands, generally resulted from either scattered trees that produced seed for subsequent stand development, or the gradual deterioration of old-growth stands from wind, insects, and diseases (Alexander 1972). The diversity complicates the modification of silvicultural systems for multiple use.

Lodgepole pine stands are frequently pure pine over much of the area it occupies, especially where stands originated after repeated fires and there is no seed source for other species (Tackle 1961a, 1965). However, mixed stands of lodgepole pine and other species are not uncommon. In pure stands of lodgepole pine of medium to high density, there is seldom an understory of reproduction; in low-density

Figure 21.—Heavy blowdown in lodgepole pine after partial cutting that removed 60 percent of the original basal area. Fraser Experimental Forest, Colorado.

stands there may be younger trees in the understory. If this advanced growth has not been suppressed for long periods of time it will respond to release.

In mixed stands, the overstory can either be pure pine, or pine, spruce and/or fir at higher elevations, and pine and Douglas-fir at lower elevations, with the climax species in the understory. Advanced growth of the climax species will respond to release when the overstory is removed (Alexander 1972).

PAST CUTTING HISTORY

Cuttings in lodgepole pine forests date back almost 100 years. Some of the earliest were clearcuttings to provide stulls, lagging, and charcoal for mining operations. Pioneer ranchers used lodgepole pine for fuel, fences, and corrals. Later, millions of cross ties were hewn for the railroads. Following World War I, some form of partial cutting became standard practice on the National Forests of the central Rocky Mountains, even though early studies suggested that clearcutting satisfied the silvical requirements of the species (Bates et al. 1929, Clements 1910, Mason 1915b). The usual practice was to mark stands for the selective removal of special products. Cutting was often heavy because everything salable was frequently marked for removal. Most skidding was done with horses, and seedbed preparation was limited to the disturbance associated with logging and slash disposal. Slash was either lopped and scattered or piled and burned (Thompson 1929).

Heavy partial cutting in general (removal of more than 50 percent of the total basal area), and under some conditions any kind of partial cutting, was not successful as a means of arresting deterioration in old-growth stands or accelerating growth of the residual stand. For example, residual trees on the Fraser Experimental Forest suffered heavy mortality when about 60 percent of the total basal area was removed by either individual tree selection or modified seed-tree cutting (Alexander 1966b) (fig. 21). Furthermore, net increment was less than in uncut stands. Similar results followed heavy partial cutting elsewhere in the central Rocky Mountains, and in the northern and C nadian Rockies (Blyth 1957, Hatch 1967, LeBarron 1952). Even where mortality was not a serious problem, heavy partial cutting often left the older, decadent stands in such poor condition that not only was there little or no growing stock available for another cut, but the stands had little appearance of permanent forest cover (Tackle 1965).

The principal cause of mortality was usually windfall, and it generally increased as the intensity of cutting increased. Mountain pine bee-

tle (*Dendroctonus ponderosae* Hopk.) outbreaks caused heavy losses in some instances, and beetles continue to be a serious and often unpredictable threat to lodgepole pine forests. In addition, many stands were infected with dwarf mistletoe (*Arceuthobium americanum* Nutt. ex. Engel.). Partially opening up the stand intensified the infection on residual trees, which in turn infected the new reproduction, leading to infection centers in the next generation. These heavily dwarf mistletoe-infected stands are a serious lodgepole pine management problem (Gill and Hawksworth 1964).

Where substantial reserve volumes were left, partial cutting was successful in some instances in the sense that the residual stand did not blow down. On the Fraser Experimental Forest, windfall losses were light and other mortality negligible after partial cutting removed about 45 percent of the total basal area by a modified shelterwood cut, even though the stands were exposed to windstorms that nearly destroyed adjacent, partially cut stands with less residual basal area (Alexander 1966b). Net increment was no greater than in uncut stands, however.

There are numerous examples of early cuttings on many National Forests in Colorado and Wyoming where a light to moderate shelterwood cut that removed 30 to 40 percent of the total basal area did not result in excessive mortality. The openings created have regenerated to either new lodgepole pine or the climax species. Where dwarf mistletoe infection in overstory trees was light, the new pine stand is not heavily infected. Similar stands have originated from open-grown trees and stands that were opened up by mountain pine beetle infestations (Alexander 1972).

In 1939, Taylor developed a tree classification scheme for marking lodgepole pine for partial cutting that is still useful today (fig. 22). He based his classification on the area, length, and vigor of the crowns of individual trees:

Vigor class A

1. Crown area: 30 percent or more of the "extreme outline" of vigor class A.
2. Crown length: 50 percent or more of the bole length.
3. Crown vigor: Dense, full, good color, pointed.

Vigor class B

1. Crown area: Usually more than 30 percent but less than 50 percent of the "extreme outline" of vigor class A.
2. Crown length: Usually more than 50 percent but usually less than 60 percent of the bole length.
3. Crown vigor: Moderately dense, good color, pointed or slightly rounded.

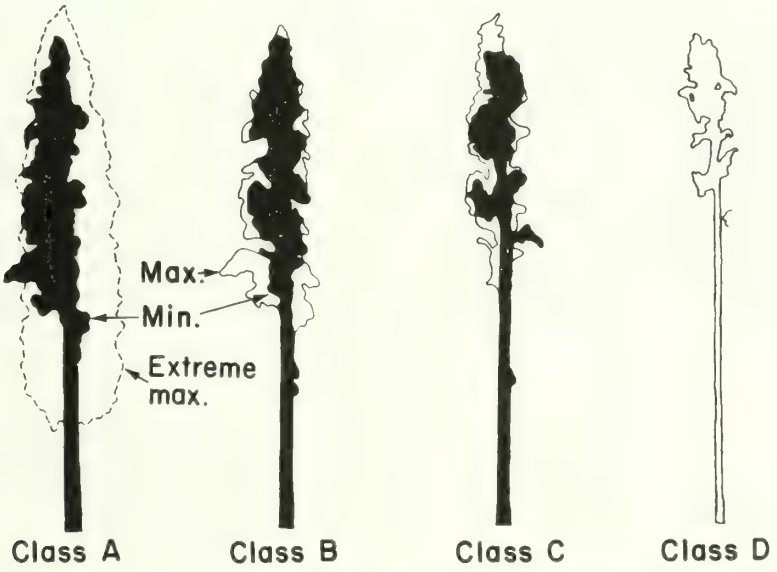

Figure 22.—Tree vigor classes (Taylor 1939).

Vigor class C

1. Crown area: 15 to 30 percent of the "extreme outline" of vigor class A.
2. Crown length: 40 to 50 percent of the bole length except for trees with above average vigor, when 20 percent of the bole length is sufficient.
3. Crown vigor: Sparse, bunchy, poor color, never pointed.

Vigor class D

1. All live trees of poorer vigor than class C. Includes trees in classes A, B, and C outlines but with dead or dying tops.

At the close of World War II, harvesting shifted back to clearcutting as the recommended practice (LeBarron 1952, Lexen 1949). Traditionally, stands have been clearcut in either blocks or strips (Alexander 1966b, LeBarron 1952, Lexen 1949, Tackle 1965). The pattern and size of opening depended upon the predominant cone habitat (serotinous or nonserotinous) and the occurrence of dwarf mistletoe (Tackle 1965). The common practice has been to cut all merchantable trees, followed by removal of the unmerchantable residual to reduce dwarf mistletoe infection. Slash and logging debris have usually been either (1) broadcast burned, dozer piled or windrowed and burned, or (2) roller chopped to reduce fire hazard and prepare seedbeds. Clearcuts have usually restocked naturally if logging slash bearing serotinous cones was carefully handled (Alexander 1966a; Boe 1956; Tackle 1964, 1965), or openings were small where cones were nonserotinous (Alexander 1966a). However, both artificial and natural regeneration efforts have failed where seed was burned in slash fires, openings were too large to be seeded in from the side, or opening up the site created difficult microenvironments (USDA-FS 1971).

Clearcutting is still the recommended practice for areas where timber production is the primary use, but openings must be smaller (40 acres or less) than in the past, and designed to blend into the landscape. Where the visual and environmental impacts of clearcutting are not acceptable, clearcutting is not compatible with other uses, or regeneration will be difficult, some form of partial cutting must be used (Alexander 1972).

DAMAGING AGENTS

Windfall

In the central Rocky Mountains, lodgepole pine is generally considered susceptible to windthrow after cutting. Partial cutting increases the risk because the entire stand is opened, whereas only the boundaries between cut and uncut areas are vulnerable after clearcutting (Alexander 1966b, 1972; Mason 1915b). While the tendency to windthrow is frequently attributed to a shallow root system, the development of the root system varies with soil and stand conditions. On deep, well-drained soils, trees have a better root system than on shallow or poorly drained soils. With the same soil conditions, the denser the stand the less windfirm are individual stems, because trees that have developed together in dense stands over long periods of time mutually protect and support each other and do not have the roots, boles, and crowns to withstand exposure to the wind if opened up drastically. The risk of blowdown is also greater in stands with defective roots and boles. The presence of old windfalls is a good indication of lack of windfirmness. Furthermore, regardless of how stands are cut or the soil and stand conditions, the risk of blowdown is greater on some exposures than others. The following windfall risk situations based on exposure have been identified by Mason (1915b) and Alexander (1964, 1967a, 1972):

Low Windfall Risk Situations

1. Valley bottoms except where parallel to the prevailing winds, and all flat areas.
2. All lower and gentle middle north- and east-facing slopes.
3. All lower and gentle middle south- and west-facing slopes that are protected by considerably higher ground not far to windward.

Moderate Windfall Risk Situations

1. Valley bottoms parallel to the direction of prevailing winds.
2. All lower and gentle middle south- and west-facing slopes not protected to the windward.
3. Moderate to steep middle and all upper north- and east-facing slopes.
4. Moderate to steep middle south- and west-facing slopes protected by considerably higher ground not far to windward.

High Windfall Risk Situations

1. Ridgetops.
2. Moderate to steep middle south- and west-facing slopes not protected to the windward, and all upper south- and west-facing slopes.
3. Saddles in ridgetops.

The risk of windfall in these situations is increased at least one category by such factors as

poor drainage, shallow soils, and defective roots and boles. All situations become high risk if exposed to special topographic situations such as gaps and saddles in ridges at higher elevations to the windward that can funnel wind into the area.

On clearcut units the leeward cutting boundaries are the most vulnerable, especially if they are at right angles to the direction of windstorms.

Insects

Many species of insects infest lodgepole pine (Keen 1952), but the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) is the most serious pest in mature to overmature lodgepole pine stands in the Rocky Mountains. Epidemics have occurred throughout recorded history (Roe and Amman 1970), and extensive outbreaks are now in progress in northern Wyoming. Less extensive, but severe outbreaks are underway in southern Wyoming and northern Colorado, where a large number of old-growth stands that have been protected from wildfires are now reaching a high degree of susceptibility to attack (Alexander 1972).

Mountain pine beetles feed and breed in the phloem layer. The first indications of attack are pitch tubes on the trunk where beetles have entered, and boring dust in the bark crevices and around the base of the tree. Trees successfully attacked in the summer usually begin to fade the following spring. Needles change from green to yellow green, sorrel, and finally rusty brown before dropping off (McCambridge and Trostle 1972).

Not all stands are equally susceptible to attack. Epidemic outbreaks are usually associated with stands that contain at least some vigorous, thick-phloemed trees 14 inches in diameter and larger (Cole and Amman 1969, Roe and Amman 1970). As the larger trees are killed, the beetles must attack smaller diameter trees until the outbreak finally subsides because the phloem of these trees is not thick enough to provide a food supply. Trees smaller than 6 inches d.b.h. are rarely killed. Although natural factors such as a sudden lowering of fall temperature or prolonged subzero winter temperatures, nematodes, woodpeckers, and parasites may reduce populations, they cannot be relied upon to control outbreaks (McCambridge and Trostle 1972). Chemical control is expensive and often is only a holding action until potentially susceptible trees can be disposed of by other means.

The only alternatives left to the manager in heavily infested stands where most of the trees are 10 inches in diameter and larger are to (1) fell and salvage the infested trees, burn the green culls and unmerchantable portions of trees, and regenerate a new stand, or (2) let the infestation run its course uncontrolled. On the other hand, in infested stands with a good stocking of trees in the smaller diameter classes, partial cutting that removes the vigorous, larger trees with thick phloem appears well adapted to regulating mountain pine beetle losses.

The pandora moth (*Coloradia pandora* Blake) (Carolin and Knopf 1968) and the lodgepole terminal weevil (*Pissodes terminalis* Hopk.) that produce distorted or forked crowns in young stands are other potentially serious insects attacking lodgepole pine.

Diseases

Dwarf mistletoe is the most serious disease affecting lodgepole pine (Hawksworth 1965) (fig. 23). Surveys in Colorado and Wyoming show that from 30 to 60 percent of the commercial lodgepole pine forests are infected to some degree by dwarf mistletoe (Hawksworth 1958). Dwarf mistletoe reduces growth, increases mortality (Hawksworth and Hinds 1964), and drastically reduces seed production. The mortality rate depends largely on the age of the host tree when attacked. Young trees die quickly, while older trees with well-developed and vigorous crowns may not show appreciable effects for years. Dwarf mistletoe is most damaging in stands that have been partially opened up by cutting, mountain pine beetles, or windfall, and of least consequence on regenerated burns following catastrophic fires (Gill and Hawksworth 1964). Heavily infected old-growth stands frequently have only about half the fbm volume of comparable uninfected stands (Hawksworth 1958).

The disease is difficult to detect in recently infected stands because trees show no abnormalities except for the inconspicuous shoots on branches and main stems. Where the parasite has been present for a long time, stands will have one or more heavily damaged centers characterized by many trees with witches' brooms, spike-tops, and an above-average number of snags with remnants of brooms (Gill and Hawksworth 1964).

Although optimum development is favored by a vigorous host, and the most vigorous trees are most heavily infected, the frequency of infection is usually higher on poor than good sites. Furthermore, where site index is 70 or greater (Alexander 1966c), only the middle and lower crowns of dominants and codominants are susceptible to heavy infection, while trees in the

Figure 23.—Dwarf mistletoe-infected lodgepole pine. Bighorn National Forest, Wyoming.

intermediate or lower crown classes are susceptible to heavy infection throughout their crowns. Where the site index is below 70, all crown classes are susceptible to heavy infection throughout the crowns.[15] In Colorado and Wyoming, dwarf mistletoe has an altitudinal limit about 300 to 500 feet below the upper limit of commercial lodgepole pine forests. This means that in some areas, considerable lodgepole pine lies in a dwarf mistletoe-free zone (Gill and Hawksworth 1964).

Separation of the old and new stands by clearcutting and felling unmerchantable residual trees appears to be the best way to control dwarf mistletoe. In areas of high tree values, such as recreational, administrative, and homesites, infected branches can be pruned from lightly infected trees, but heavily infected trees must be cut. Partial cutting and thinning generally create ideal conditions for maximum damage, and should be avoided where possible unless the infection is light.

To quantify the severity of infection, Hawksworth (1961) developed the 6-class mistletoe rating system (fig. 24). The average stand rating can be estimated by determining the percentage of trees infected in the stand. The approximate relationship of average stand rating to proportion of trees infected in several mature stands was:

Average stand mistletoe rating	Percent of trees infected
1	50
2	70
3	90
4	97
5	99
6	100

Comandra blister rust, a canker disease caused by *Cronartium comandrae* Pk., occurs commonly in the central Rocky Mountains, but damage has been most extensive in northern Wyoming (Peterson 1962). Girdling causes dead tops and flagging branches, which are the most conspicuous symptoms until dead trees begin to appear. On larger stem infections, cankers with an abundance of yellow, dried resin are a conspicuous symptom (Mielke et al. 1968). The disease cannot pass directly from pine to pine but requires an intermediate host (*Comandra umbellata* (L.) Nutt.).

The damage from Comandra rust is usually not spectacular, but trees of all sizes and ages

[15] *Personal communication with Frank G. Hawksworth, Plant Pathologist, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

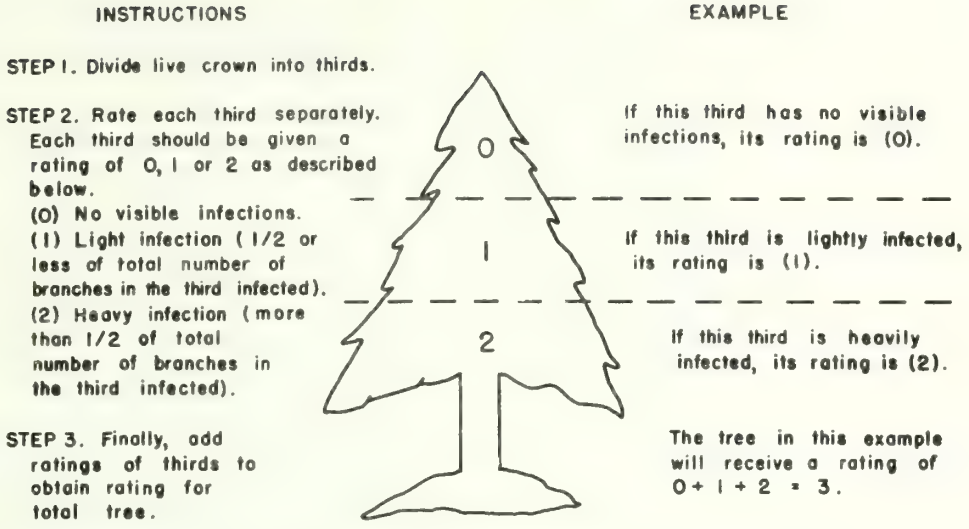
INSTRUCTIONS
EXAMPLE
STEP 1. Divide live crown into thirds.
STEP 2. Rate each third separately. Each third should be given a rating of 0, 1 or 2 as described below.
(0) No visible infections.
(1) Light infection (1/2 or less of total number of branches in the third infected).
(2) Heavy infection (more than 1/2 of total number of branches in the third infected).
STEP 3. Finally, add ratings of thirds to obtain rating for total tree.
0
1
2
If this third has no visible infections, its rating is (0).
If this third is lightly infected, its rating is (1).
If this third is heavily infected, its rating is (2).
The tree in this example will receive a rating of 0 + 1 + 2 = 3.

Figure 24.—The 6-class mistletoe rating system (Hawksworth 1961).

are susceptible (Peterson 1962). Seedlings may be killed in a relatively short time. In older trees, the time betwen initial infection and death may be 25 or more years because the infection enters the trunk by way of the branches and the rate of spread is slow. Under conditions favorable to the rust, stands may be heavily damaged over limited areas. In those stands, from 30 to 40 percent of the living and dead trees will have cankers, and about half the cankered trees will have spike-tops (Krebill 1965). Usually, however, the infection is lighter and scattered through the stand (Peterson 1962).

Sanitation salvage cutting is about the only practical way of controlling the disease in forest stands (Mielke et al. 1968). In areas of high tree values it may be possible to prune infected branches from lightly infected trees, but heavily infected trees should be cut. Partial cutting and thinning appear well adapted to the control or reduction of Comandra rust, even in heavily damaged stands, because the disease is not passed from pine to pine and only the trees with stem infections need to be removed.

Western gall rust (*Peridermium harknessii* Moore) occurs on lodgepole pine throughout the Rocky Mountains, but is not as distinctive as Comandra rust because most infections occur as galls on branches rather than on the trunk. Mortality in the seedling stage and loss of growth and cull are the principal forms of damage from this rust. Removal of infected trees in cultural operations is the only practical way to control gall rust damage in forests. Presence of a few galls is not sufficient cause to remove a tree. Only cankered trees need be cut (Peterson 1960).

The major root and butt fungi attacking lodgepole pine in the Rocky Mountains are *Polyporus circinatus* Fr., *Coniophora puteana* (Schum ex. Fr.) Karst, and *Armillaria mellea* (Fr.) Quel.; the principal trunk rot fungus is *Fomes pini* (Fr.) Karst (Hepting 1971, Hornibrook 1950).

NATURAL REGENERATION REQUIREMENTS

The basic elements necessary for successful natural regeneration are the same as for spruce: (1) an adequate supply of viable seed, (2) a suitable seedbed, and (3) environmental conditions compatible with initial survival and seedling establishment.

Seed Supply

FLOWERING AND FRUITING

Male flowers of lodgepole pine ripen and pollen is wind disseminated in late spring and early summer. Cones from the current year's crop mature and seed ripens in September and October (Tackle 1961a).

CONE BEARING AGE

Lodgepole pine begins bearing cones with viable seeds at a very young age — in open stands by trees 5 to 10 years old, in more densely stocked stands by age 15 to 20 years — and continues well past maturity (Crossley 1956b,

Table 3.--Variations in serotinous cone habit and estimated average sound seed per acre stored in serotinous cones on four areas in Montana and Idaho (Lotan 1967a, 1968)

Average age of stand, (yrs)	Cone habit			Average sound seed stored per acre
	Predominately serotinous	Intermediate	Predominately nonserotinous	
	Percent of trees			*Millions*
111 (uneven aged)	38	14	48	1.0
88 (even aged)	58	10	32	3.2
117	48	19	33	1.8
191	23	20	57	.8

Tackle 1961a). Seed from trees less than 10 years old can have as high a germination percentage as seed from mature trees.

CONE CHARACTERISTICS

The regeneration of lodgepole pine is greatly affected by its cone habit. Individual trees are classified as (1) **closed cone** if 90 percent or more of the cones are serotinous, (2) **intermediate** if less than 90 but more than 10 percent of the cones are serotinous, and (3) **open cone** if less than 10 percent of the cones are serotinous (Crossley 1956b; Lotan 1967a, 1968).

Throughout much of the Rocky Mountains, the closed cone habit is widespread (Alexander 1966a, Critchfield 1957, Tackle 1961a). In stands with the serotinous habit, trees bear an abundance of closed cones that remain unopened on standing trees up to 40 years (Lotan and Jensen 1970). That seed is available for release following fire or cutting. In one study over a 10-year period in central Colorado and southern Wyoming, the average amount of seed stored in closed cones was 2½ to 3½ times greater than the current crop (Bates 1930). The average number of sound seeds stored in closed cones ranged from 181,000 to 1,104,000 per acre.

Although most trees bear either serotinous or nonserotinous cones, the number of serotinous cones varies greatly from tree to tree, and the proportion of closed-cone types varies greatly between stands (Clements 1910, Mason 1915a, Lotan 1967a). Lotan (1967a, 1968) studied the variation in serotinous cone habit and estimated the number of sound seeds stored in closed cones on four areas in Montana and Idaho (table 3). Most trees produced almost entirely either open or closed cones. Only 10 to 20 percent of the trees were classified as intermediate. The estimated number of sound seeds stored in closed cones varied from 0.8 to 3.2 million per acre.

The fruiting habits of lodgepole pine in Alberta suggest a possible relationship of age to closed cone habit (Crossley 1956b). In young stands (17 years old) only 17 percent of the trees had closed cones, while in 55- and 250-year-old stands, 82 and 83 percent, respectively, of the trees bore closed cones.

In some areas the cone habit is known to be nonserotinous. For example, trees in northern Wyoming on the Bighorn and Shoshone National Forests bear largely open cones. Other areas reporting mainly nonserotinous cones are the Deschutes Basin and Blue Mountains in Oregon (Dahms 1963, Mowat 1960, Trappe and Harris 1958).

The variability in closed cone habit means that each stand must be examined before cutting to determine cone serotiny and estimate the number of sound seeds available in closed cones. Lotan and Jensen (1970) have developed such estimating procedures from data collected in mature and overmature stands in Idaho and Montana. They should also provide reasonable estimates of the number of sound seeds stored in serotinous cones in similar stands in the central Rocky Mountains, however. Seed from nonserotinous cones can be estimated from conventional seed traps.

TIME OF SEEDFALL

Natural seedfall in lodgepole pine occurs throughout the year, but not at a uniform rate. On two study areas in pure, overmature stands in Montana, only about 20 percent of the yearly crop shed was released during August and September in 3 out of 4 years; 60 to 70 percent was shed from October to June the following year, and the remainder fell in June and July (Boe 1956, Tackle 1964). In the subalpine forest region of Alberta, maximum annual seedfall during 3 years of observation in a 60-year-old stand occurred over a 4- to 5-week period,

and was heaviest the first week in October (Crossley 1955). In eastern Oregon, most of the seedfall occurs before November (Dahms 1963, Mowat 1960).

PRODUCTION AND PERIODICITY

Lodgepole pine has generally been rated a prolific seed producer, with good crops borne at 1- to 3-year intervals and light crops produced in the intervening years (Bates 1930, Dahms 1963, Mason 1915a). On the other hand, Boe (1954) analyzed cone crop records in Montana, and rated the 16 crops observed during a 45-year period west of the Continental Divide as 1 good, 11 fair, and 4 poor. East of the Divide, seed crops were rated 2 good, 13 fair, and 5 poor for a 20-year period. Part of the apparent differences in seed production may be in definitions of what is a good seed year, however.

The number of fully developed seeds per cone varies widely. In one study on 9 National Forests in Colorado and Wyoming, cones averaged 26 seeds (Mason 1915a). Cones averaged 40 seeds in another study of large lots of cones in Colorado and southern Wyoming, but individual cones produced as few as one or two seeds (Bates 1930). The average number of sound seeds per cone in Montana and Idaho varied between 10 and 20 (Lotan 1967a, 1968).

Seed production by individual trees and by stands also varies considerably. Seeds from old and new cones together averaged 50,000 per tree in Idaho and 21,000 per tree in Colorado (Clements 1910). Annual variations in seed production on felled trees during a 10-year period (1912-21) ranged from 0 to 135,000 per acre in southern Wyoming, and from 55,000 to 827,000 per acre in central Colorado (Bates 1930). In central Oregon, where the cones are nonserotinous and the total crop is released each year, annual production in uncut stands varied from 178,000 to 572,000 sound seeds per acre during a 3-year period (Dahms 1963). In the other year of the study, only 14,000 seeds per acre were produced.

In Montana, annual seedfall in stands with predominately serotinous cones averaged 70,000 sound seeds per acre over a 4-year period (Boe 1956). Tackle (1964) observed this Montana area for 2 more years and another area nearby for 2 years, and reported average annual release of 65,000 to about 90,000 sound seeds per acre. In similar stands in Alberta, average annual seedfall varied from 10,000 to 30,000 seeds per acre during a 3-year period (Crossley 1955). Most of the seed released in the predominately serotinous stands probably came from nonserotinous cones, and represents only a small proportion of the annual seed production in these stands.

SEED QUALITY

Variability in seed quality affects sound seed production. Bates (1930) concluded that the percentage of sound seed was higher in years of good seed production than in years of poor production. Furthermore, more sound seeds were available from current cones than from old cones. On the other hand, a number of studies have indicated little difference in seed quality between new cones and those up to 10 years old (Ackerman 1963, Crossley 1956a, Lotan 1964b). About 50 percent of the stored seed was viable in one study (Lotan 1964b). No data are available for seed from nonserotinous cones.

DISPERSAL

Lodgepole pine seed is light, averaging about 100,000 seeds per pound, with about 1/3 to 1/2 pound of seed per bushel of cones (Bates 1930). Dispersal from standing trees is largely by wind, but wind is important only in stands where nonserotinous cones are abundant (Tackle 1961a). Seedfall into cleared openings has been studied in Montana and Oregon (Boe 1952, 1956; Dahms 1963, Tackle 1964). Seed dispersed from standing timber dropped off sharply at a distance of about 66 ft and continued to diminish as distance from the source increased. These authors concluded that the number of seeds dispersed beyond 200 ft from the source was inadequate to restock a cutover area regardless of the amount of seed released under the uncut stand. More seeds were dispersed from the north and west boundaries than from the south and east boundaries on most areas studied, but differences were too small to detect any influence of prevailing winds on seed dispersal.

In Alberta, Crossley (1955) found a somewhat different dispersal pattern. Although the number of seeds falling to the ground diminished as distance from standing timber increased, seedfall did not diminish as rapidly in the first 66 ft, and there was little difference in the number of seeds falling to the ground between 66 and 330 ft from standing timber. He also concluded, however, that the amount of seed falling into the opening was not adequate to restock the area.

Seeds released from cones attached to the slash and cones knocked from the slash and

scattered on the forest floor are the most important in regenerating stands with serotinous cones (Tackle 1961a). Most seeds are released from this source the first year after exposure (Boe 1956, Crossley 1956a). Some seeds are released for as long as 6 years (Tackle 1954b) but the number is not likely to be significant after the second year because there is little further change in cone radiation, height above the ground, or ventilation (Crossley 1956a). Furthermore, seeds from cones lying on the ground for as long as 6 years have only about half the germinative capacity of seeds stored in cones above the ground for the same period of time (Tackle 1954b).

Fire is not a requisite for seed release from closed cones in the slash (Bates et al. 1929), but heat is necessary. Temperatures of at least 113° to 122° F are required to melt the resin bond and allow cone scales to flex and spread apart (Cameron 1953, Clements 1910). Crossley (1956a) investigated the effects of solar radiation on cone opening, and found that an air temperature of at least 80° F at 3.5 ft above the ground was necessary to provide the heat needed to rupture the bonds of cone scales. Furthermore, the cones had to be on or near the ground surface to open, because at heights above 7 inches from the ground or other reflecting surface, cone temperatures did not rise sufficiently to melt resin bonds. More cones open on south slopes than on north slopes, but the amount of residual overstory apparently has little effect on cone opening because only a short exposure to direct solar radiation is sufficient to raise temperatures to a critical level (Crossley 1956a, Lotan 1964b).

No data are available from the central Rocky Mountains on the number of sound seeds required to produce an established seedling under different seedbed and environmental conditions. Lotan (1964a, 1968) has suggested that, under favorable seedbed and environmental conditions in the northern Rocky Mountains, 30,000 to 50,000 sound seeds per acre are needed to produce 1,000 first-year seedlings.

In stands with serotinous cones, assuming that Lotan's figures are reasonable estimates, the amount of seed stored in closed cones appears to be more than adequate to insure regeneration success if logging slash bearing cones is carefully handled. In stands with nonserotinous cones, 30,000 to 50,000 sound seeds per acre are not likely to be dispersed as far as 200 ft from standing timber in any one year. This suggests that the maximum size of opening in a nonserotinous stand that will restock in a reasonable amount of time is probably no greater than 300 ft wide or about four to five times tree height.

SOURCE

There are several sources of seed available for natural reproduction (Tackle 1964). In clearcut openings, the principal sources are:

1. Serotinous cones in the logging slash (provides only a one-shot opportunity).
2. Nonserotinous cones on trees standing around the cleared opening (wind disseminated about 150 ft).
3. Nonserotinous cones on unmerchantable residual trees while they are still standing.
4. Nonserotinous cones on new reproduction 5 to 10 years old.
5. Some seed is also available from nonserotinous cones on trees cut on the area.

In partially cut areas, the principal sources of seed are from serotinous cones in the logging slash and from nonserotinous cones on residual trees left on the area. Some seed may also be available from nonserotinous cones on trees cut on the area.

One of the significant considerations in clearcutting in stands with nonserotinous cones is the resistance of the seed source to windthrow. Situations and conditions where windfall risk is low, moderate, and high have been identified (Mason 1915a) and recommendations developed for locating windfirm boundaries on clearcut units (Alexander 1964, 1967b). These recommendations have been modified to identify the kinds of trees and residual volumes that can be successfully retained in partially cut areas for different windfall risk situations and stand conditions (Alexander 1972).

VIABILITY

The viability of lodgepole pine is rated good. In a series of 413 uniform tests, an average germinative capacity of about 80 percent was obtained after 41 days at 6 to 10 percent moisture with fluctuating diurnal temperatures of 57° to 83° F (Bates 1930). Lodgepole pine will retain a good germinative capacity for long periods of time if properly stored. The germinative capacity of seed stored in serotinous cones is not seriously reduced even after 50 to 75 years (Clements 1910 , Tackle 1954b). Lodgepole pine seed does not normally require pretreatment, but stratification may hasten germination (Tackle 1954b). In nature, lodgepole pine seed overwinters under the snow and germinates the following spring.

SEED LOSSES

Lodgepole pine seed crops are subject to losses before seedfall to cone and seed insects (Keen 1958), but their relative importance, frequency of occurrence, and magnitude are not known. Pine squirrels consume large amounts of seed and cones, as evidenced by the large caches common to lodgepole pine forests. After seed is shed to overwinter, small mammals such as mice and chipmunks undoubtedly consume considerable but unknown amounts of seed. In western Montana, lodgepole pine seedlings survived better on protected than on unprotected spots, but the differences may have been due to factors other than rodents (Roe and Boe 1952, Tackle 1961b). In the interior of British Columbia, protection from rodents was essential to lodgepole regeneration success (Prochnau 1963).

Factors Affecting Germination

Viable seeds of lodgepole pine that survive overwinter normally germinate in the early summer following snowmelt in the central Rockies. Optimum air temperature for germination is about 70° F (Bates 1930). Air temperatures of 70° F are usually reached in early June in the central Rocky Mountains, but snow frequently covers the seedbed until middle or late June. In one study in the northern Rocky Mountains, where seeds were sown in the fall to simulate natural seedfall, 90 percent of the germinating seedlings emerged the first 2 weeks in July following snowmelt in late June (Lotan 1964a). Field germination percentages were 74 to 84 percent for all seedbed conditions — considerably higher than reported for Colorado and Wyoming (Bates 1930).

Lodgepole pine is noted for its ability to germinate on burned surfaces after wildfire. Fire releases the seed from serotinous cones, creates a favorable seedbed, and reduces vegetative competition for light and moisture. However, site conditions and intensity of burn, as well as seed supply, influence germination on burned seedbeds. Some areas of the same burn will be overstocked, while other parts will be poorly stocked or nonstocked (Horton 1953, 1955; Stahelin 1943).

Germination has also been variable on seedbeds prepared by burning. In Colorado, good germination occurred in full sunlight on seedbeds where slash was burned in small piles (USDA-FS 1943). Good germination occurred on burned seedbeds in Alberta, but mortality on the black surfaces was high in full sunlight (Crossley 1956c). On the other hand, poor germination has been reported on burned seedbeds by Ackerman (1957), Boe (1956), and Crossley (1952). These authors did not indicate, however, whether poor success was due to high temperatures and surface drying, deep layers of loose dry ash, or loss of seed supply when cone-bearing slash was burned. In a greenhouse study, leached burned soil provided the highest germination, but unleached burned soil with a high ash content inhibited germination (Gayle and Gilgan 1951).

Germination has usually been better on exposed mineral soil and on disturbed duff and mineral soil than on other seedbed types, presumably because of more stable moisture conditions (Ackerman 1962, Bates et al. 1929, Boe 1956, Crossley 1956c, Tackle 1964, Trappe 1959). Germination has frequently been good on the natural forest floor (Boe 1956, Crossley 1956c), but the initial germination is often offset by heavy mortality when the seedbed dries out (Ackerman 1962, Prochnau 1963).

The effectiveness of the seedbed is influenced by any factor that affects temperature and moisture, as well as depth of slash and distribution of the slash-borne seed supply.

On clear days in early summer, exposed soil surfaces are rapidly dried out and heated to high temperatures. Few seeds can imbibe sufficient water to germinate, and many newly germinated seedlings are killed by stem girdle or drought. Shade either from light slash or a residual overstory reduces excessive heating and drying of the soil surface, thereby improving germination on both burned and mineral soil seedbeds (Crossley 1956c, Day and Duffy 1963). On the other hand, slash may inhibit germination if it is too deep and a mat of needles and fine twigs several inches thick accumulates (Boe 1956, Lotan 1964a, Tackle 1954b). Furthermore, if germination is delayed until late summer rains, the late-germinating seedlings may not harden off before the onset of cold weather (Ronco 1967).

Factors Affecting Initial Survival and Seedling Establishment

Most lodgepole pine seedling mortality occurs during the first growing season after germination, but seedlings usually require about 2 to 3 years after germination to become established. The first growing season is considered here to be the period of initial survival, and the second and third growing seasons as the time of seedling establishment.

INITIAL ROOT GROWTH

The rate of root growth is an important determinant in the initial survival of lodgepole pine seedlings. The further the root penetrates the soil, the better the chance for the seedling to survive drought and frost heaving. Critical rooting depth depends upon the seedbed type, weather, and soil properties.

There is little information on the first-year rooting depth of lodgepole pine other than the growth is slow (Tackle 1961a). Lotan (1964a) excavated a few seedlings less than 8 weeks old in the northern Rocky Mountains, and found roots 5 to 6 inches long on mineral soil seedbeds, 4 inches long on undisturbed duff. Seedlings initially form a weak taproot but it does not persist. The initial root system is stunted or obscured by subsequent lateral root development (Horton 1958).

SEEDBED TYPE

In the undisturbed forest, lodgepole pine seedlings establish most readily in openings on mineral soil such as upturned mounds resulting from windfall. Seedlings will become established on duff, litter, partially decomposed organic matter, or decaying wood if they are under a canopy that provides sufficient light while preventing the seedbeds from heating and drying out. Lodgepole pine seedlings do not become established in significant numbers on any seedbed type under a closed canopy.

The same seedbeds are available after logging and slash disposal, but with some additional mineral soil, and burned mineral soil and mineral soil mixed with organic matter. Removal of the overstory modifies the microhabitat, however, and such factors as organic seedbeds and competing vegetation frequently become limiting to natural regeneration success. Seedbed preparation to create a more favorable moisture source can modify limiting factors sufficiently to enable seedlings to survive.

Serotinous Cones

In stands with serotinous cones, the effect of seedbed type on survival and establishment is frequently confounded with slash disposal treatments because the seed supply is largely in the slash-borne cones. Furthermore, natural reproduction with seed from serotinous cones is a one-shot opportunity, and if the slash is not carefully handled, good seedbed conditions are wasted.

Lodgepole pine survival and establishment after logging and slash disposal in the central Rocky Mountains has generally been best on prepared mineral soil seedbeds (Alexander 1966a, USDA-FS 1943). In fact, the combination of dozer piling or windrowing slash for burning, and mechanically exposing mineral soil has frequently resulted in so much reproduction that early thinning is required to control stand density (Alexander 1966a).

Seedling survival and establishment have been good on burned seedbeds (Alexander 1966a, 1966b; USDA-FS 1943) except on fully exposed south slopes or where the seed supply has been destroyed in slash disposal. In one study in southern Wyoming, however, seedling establishment was nearly optimum on seedbeds where slash was broadcast burned or the concentrations burned, and the seed supply in serotinous cones was largely consumed by the slash fires. Seed for restocking these small (400 ft wide) openings came from nonserotinous cones on trees standing around the perimeter (Alexander 1966a).

Seedling survival and establishment has been variable on undisturbed seedbeds. On some areas it was only fair (USDA-FS 1943), but on other areas, satisfactory numbers and stocking were obtained on natural seedbeds with only a light cover of duff and litter. On the latter areas, slash was either lopped and scattered, or untreated slash was less than 1 ft deep and covered less than 40 percent of the area (Alexander 1966a, 1966b).

In the northern Rocky Mountains and Alberta, initial survival and establishment were better on mechanically scarified mineral soil and a combination of disturbed mineral soil and duff than other seedbeds (Ackerman 1957, 1962; Boe 1956; Crossley 1952, 1956c; Johnson 1968; Tackle 1965). In fact, these seedbeds were usually overstocked. Good establishment was obtained on undisturbed seedbeds on comparatively dry sites with a minimum of unincorporated organic matter and a paucity of competing vegetation, and on disturbed seedbeds where slash was lopped and scattered. Satisfactory numbers and stocking of reproduction were obtained on seedbeds with unburned slash concentrations and windrows, and where slash was piled or windrowed and burned. Burning in general created less favorable seedbeds than mineral soil unless they were shaded, however, because of excessive heating and drying. Furthermore, on burned seedbeds, seedling establishment was frequently slow during the first few years after treatment because too much of the seed supply was destroyed in slash fires (Boe 1952). Survival and establishment did not improve until the new reproduction was

large enough to provide a seed source.

On clearcut areas where slash was left untreated, seedling survival and establishment have been better on disturbed mineral soil, disturbed duff, and areas where the depth of slash was less than 1 ft than on undisturbed duff, undisturbed soil, brush and grass, and areas where the depth of slash was greater than 1 ft (Tackle 1956).

Nonserotinous Cones

Observations of seedling establishment in stands with nonserotinous cones in northern Wyoming indicate that regeneration success on cleared openings within effective seeding distance has been satisfactory on mechanically scarified mineral soil and on burned soil seedbeds where slash was either broadcast burned, or piled or windrowed and burned. Seedbeds prepared by rolling and chopping slash have been about as effective as dozer scarification. Exceptions have been on south slopes and at lower elevations, where shade appears necessary to reduce temperatures and conserve moisture.

CLIMATE

The climate of the lower subalpine and upper montane where lodgepole pine grows in the central Rocky Mountains is warmer and drier than the higher spruce-fir zone, but the climate is still characterized by extremes in solar radiation, temperature, and moisture that can limit regeneration success.

Light and Solar Radiation

Light is essential to lodgepole pine seedling survival and establishment. Seedlings do not become established in less than 10 percent full sunlight, and development is poor in less than 20 percent full sunlight (Clements 1910). Early seedling development is usually considered best in full sunlight (Day 1964, Tackle 1961a), but lower radiation levels may be necessary on severe sites to reduce mortality (Armit 1966). Under full exposure, radiation intensities can create critical temperature and moisture conditions for first-year seedling survival.

In one study on the Fraser Experimental Forest in Colorado, more than twice as many seedlings survived the first growing season on all seedbed types with 60 percent shade than in either full sunlight or 30 percent shade (USDA-FS 1943). Similar benefits from overhead shade have been observed on south slopes, and at lower-elevation tension zones between timber and grasslands. On the other hand, first-year survival of planted lodgepole pine seedlings was equally good whether shaded or exposed to full sunlight on some of the most severe sites in the central Rocky Mountains (Ronco 1970d). Furthermore, full exposure to high light intensities did not adversely affect the rate of photosynthesis. Apparently, full exposure to high radiation intensities is more critical to newly germinated seedlings than to older stages.

Temperature

Temperature has been suggested as the least important of the environmental factors limiting regeneration success (Clements 1910), but the characteristic zonal pattern of occurrence of lodgepole pine in the Rocky Mountains is usually attributed to temperature at the upper limits (Tackle 1965).

Bates (1923) rated lodgepole pine as highly resistant to heat damage, but evidence of heat injury seems to be conflicting. Temperatures of 125° to 140° F combined with a restricted moisture supply will seriously damage or kill newly germinated seedlings in the succulent stage, and heat alone will cause mortality from stem girdling when temperatures rise to 140° to 160° F (Armit 1966). When air temperature reaches 80° F in the Rocky Mountains, direct solar radiation is capable of heating exposed soil surfaces to these levels (Crossley 1956a, Day 1964). In Alberta, Ackerman (1957), Crossley (1956c) and Day (1964) indicate that early shade protection, particularly on burned and mineral soil seedbeds, would improve survival, presumably by lowering temperatures and reducing water loss from both seedlings and soil.

In the northern Rocky Mountains, however, heat girdling of newly germinated seedlings did not occur as frequently as expected, although soil surface temperatures commonly exceeded 138° F for several hours and temperatures of 150° to 163° F were observed occasionally on the surfaces of undisturbed and burned seedbeds (Lotan 1964a). At the same time, seedlings were dying from drought. In Colorado, only 2 to 3 percent of the first-year seedling mortality over a 3-year period was from heat girdling on exposed sites where surface temperatures frequently exceeded 135° F and reached as high as 160° F (Ronco 1967). Soil moisture was sufficient to prevent drought losses.

Frost can occur any month of the growing season where lodgepole pine grows, especially in depressions and cleared openings because of

cold air drainage and radiation cooling. Newly germinated seedlings are especially susceptible to damage from early fall frosts. In a laboratory study, first-year seedling susceptibility to frost damage was affected by age as well as minimum temperature (Cochran and Berntsen 1973). Seedlings 6 weeks old were more susceptible to frost damage at night temperatures of 18° F than were seedlings 1 to 4 weeks old. At 2 months of age, all seedlings were killed by night minimums of 15° F. Previous exposure to near-freezing temperatures reduced mortality when seedlings were exposed to night minimums of 20° F or less.

Frost damage after the first year has not been observed or reported in the central Rocky Mountains (Ronco 1967).

The combination of warm daytime temperatures, nighttime temperatures below freezing, and saturated soils unprotected by snow cover in the early fall are conducive to frost heaving. In one study in central Colorado, these conditions were observed in 1 out of 3 years, and frost heaving was the principal cause of first-year seedling mortality on exposed mineral soil (Ronco 1967). Seedlings continue to be susceptible to frost heaving after the first growing season. Shading seedlings reduced mortality by reducing loss of radiant energy from both seedlings and soil.

Moisture

The moisture condition of the seedbed during the growing season largely determines first-year seedling survival. In the Rocky Mountains, summer drought can be a serious threat to seedling survival and establishment on some sites. For example, mortality to both natural and planted seedlings on south slopes in northern Wyoming has been attributed largely to drought. In Montana and Idaho, approximately 90 percent of the first-year seedling mortality in one study was caused by drought (Lotan 1964a). On the other hand, Ronco (1961b, 1967) observed the survival of newly germinated and planted seedlings over a period of years, and concluded that drought was not a serious cause of mortality in the subalpine of central Colorado. However, his studies were at a higher elevation in the spruce-fir zone where moisture is generally more abundant.

Precipitation during the growing season is particularly critical to the survival of seedlings. Lotan (1964a) found that from 50 to 70 percent of the total mortality in 1 year occurred between June 22 when germination started and July 13, a period when precipitation was negligible. Mortality was substantially reduced after more than 1 inch of rain fell beginning on July 13. The relatively few losses to drought recorded by Ronco (1961b, 1967) were attributed to frequent showers after germination began or seedlings were planted.

Summer precipitation is not always a benefit to seedling survival and establishment, especially if storms are so intense that most of the moisture runs off and soil movement on unprotected soil surfaces either buries the tops or uncovers the roots of seedlings.

SOIL

Lodgepole pine grows on a wide range of soils throughout the Rocky Mountains (Johnson and Cline 1965, Retzer 1962), but little is known about how soils affect establishment and growth (Tackle 1965). In general, lodgepole pine becomes established most readily and makes best growth on moist, light, well-drained, sandy or moderately acid gravelly loam soils derived from granites, shales, sandstones, and coarse-grained lavas (Tackle 1961a, 1965). It does not establish readily in the central Rocky Mountains on soils derived from limestone or fine-grained igneous rocks (Bates 1917a). The former are too dry, and the latter break down into clays that are too poorly drained. Lodgepole pine is generally better able to establish on dry, rocky soils, on excessively drained light-textured soils, and severe exposures than are associated species, but it does not establish readily on sites with impeded drainage or heavily acid soils.

DISEASES

Newly germinated seedlings are killed by damping-off fungi. Losses normally occur early in the growing season before seedlings cast their seedcoats, and can be serious on all seedbed types if they remain damp for long periods of time. In one study, about 14 percent of the newly germinated lodgepole pine seedlings were killed in 2 consecutive years by damping-off on mineral soil seedbeds (Ronco 1967). Snowmold fungi occasionally damages or kills both natural and planted lodgepole pine seedlings. Ronco (1967) found little damage on pine plantings except during 1 year when snowmelt was retarded and seedlings remained under the snow too long. About 20 percent of the seedlings suffered damage, which was about equally divided between shaded and open-grown seedlings.

ANIMAL DAMAGE

Ronco (1967) found that mountain pocket gophers destroyed some planted seedlings each year, but losses were highest during a population peak the third and fourth winters after planting. Nearly all seedlings destroyed by gophers were clipped just above the ground level, but a few died from root destruction caused by burrowing. Clipping damage to newly germinated seedlings while the seedcoat is still attached frequently has been attributed to mice, but there is no documented evidence of mice having actually done the damage. A recent study of clipping damage and mortality to spruce seedlings on the Fraser Experimental Forest in Colorado has demonstrated that the gray-headed junco is responsible (Noble and Shepperd 1973). It seems likely that juncos or other seed-eating birds are responsible for similar damage to lodgepole pine. The mountain vole, however, will debark and kill established seedlings.

Young lodgepole pine seedlings are vulnerable to trampling damage from grazing and browsing animals. In one study of natural reproduction in southern Wyoming (Alexander 1966a), seedbed and slash disposal treatments created easy travel routes, and cattle frequently were observed to trail through the study area. While few seedlings were trampled to death, they were either deformed or damaged to the extent that they were susceptible to woodrotting fungi.

GROUND VEGETATION

Most studies of lodgepole pine regeneration have indicated that competing vegetation is a major constraint to successful establishment (Ackerman 1962, Boe 1956, Crossley 1956c, Lotan and Dahlgreen 1971, Tackle 1964). No benefits from understory vegetation of the kind that would provide protection for newly germinated seedlings has been reported.

SITE QUALITY

Site quality is commonly used to express the productive capacity of different forest environments. Determination of productivity is basic to the prediction of yields, the establishment of optimum levels of growing stock, and consequently, the level of management that can be profitably applied to any area.

Conventional Determination

The measure of tree growth usually found most independent of stand factors, and therefore the most reliable index of site quality, is the average height of dominant trees in relation to age. The relationship of height and age, when expressed as dominant height in feet at some specified reference age, is the familiar "site index" that has come into general use as the conventional measure of site quality.

The height growth of most conifers is independent of stand density over a wide range of stocking. The family of site-index curves developed for those species simply expresses the relationship between height growth and the independent variables of site quality and age. The rate of height growth of lodgepole pine, however, is influenced by stand density probably more than any other North American conifer (Holmes and Tackle 1962, Smithers 1956). For lodgepole pine, therefore, a third variable — stand density — must be considered.

Curves and tables of the height, age, and density relationships of dominant lodgepole pine (Alexander 1966c, Alexander et al. 1967) are suitable for estimating site index at base age 100 years where total age is at least 30 years and density ranges from CCF (Crown Competition Factor) 125 or less to CCF 500 (Krajicek et al. 1961) (fig. 25). Data for these curves came from the stem analyses of 1,048 dominant lodgepole pines on 262 plots in the western United States, sampled to represent a wide range of age, site quality, and density.[16]

[16] *Equations and computer subroutines for estimating site quality have been developed by Brickell (1970) from these curves, but the base age was changed to 50 years.*

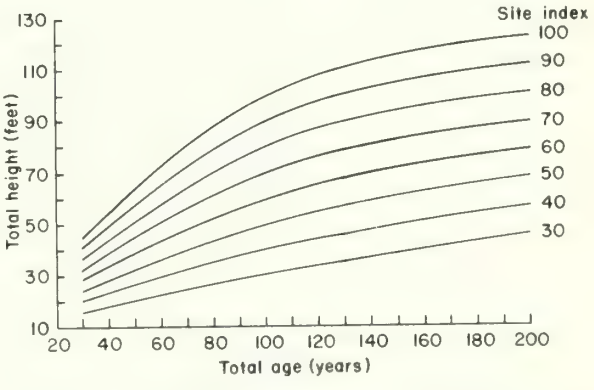

Figure 25.—Site index curves for lodgepole pine at CCF levels of 125 or less. Base age: 100 years total age.

When these site index curves or tables are used, the steps below should be followed (detailed procedures are outlined by Alexander 1966c):

1. Determine average height and age of the stand. Select four or more dominants (site trees) and measure heights and ages in the conventional manner. Average total age may be approximated by adding 9 years to the average age at breast height.
2. Determine the density of the stand in which the "site trees" developed, either by estimating CCF from (1) measurements of stand diameters or (2) measurements of basal area and average stand diameter.
3. Determine site index from the appropriate curves or tables, based on the average height and age determined in step 1 and the CCF determined in step 2.

Trees — in addition to being dominants — and stands should meet the following specifications:

Stands

1. Even-aged — not more than 20 years spread in the age of dominant trees.
2. At least 30 years old, but not more than 200 years old (at least 50 years old in Pacific Northwest).
3. Apparent site the same throughout the stand. Site will be considered the same if all trees are growing on similar topography, slope, aspect, and soils.

Site Trees

1. Located in an area in the stand where present density is uniform, and there have been no abrupt changes in past density.
2. Increment cores show a normal pattern of ring widths from pith to cambium.
3. Reasonably free of dwarf mistletoe or other diseases or injuries that may reduce height growth.
4. Sound enough for ring counts.
5. Show no visible evidence of crown damage, or tops that are broken, forked, and so forth.

Determination from Soil and Topography

Conventional methods of site determination cannot be used on lands that are nonforested or contain trees either too young or unsuitable for site determination. An alternative approach is to evaluate environmental factors that influence site productivity, and combine these into a predictive equation.

Site index of lodgepole pine in north-central Colorado and south-central Wyoming can be estimated from environmental factors using procedures developed by Mogren and Dolph (1972). Data came from 72 plots in pure, even-aged (70- to 150-year-old) stands on the Medicine Bow, Roosevelt, and Arapaho National Forests. The prediction equation is:

$$Y = 64.99 - 0.345X_1 \text{ to } .339X_2 - 0.458X_3 \underline{+} 0.436X_4$$

Where

Y = site index in feet,

X_1 = percent by weight of particles larger than 0.25 mm in diameter in the A horizon,

X_2 = total soil depth to the C horizon in inches,

X_3 = estimate of surface stoniness in percent, and

X_4 = average annual precipitation in inches.

$S_{\bar{y}\cdot x} = \pm 8.0$ ft, $R^2 = 0.78$

Estimates of site index from these environmental factors apply only to the point sampled, but in practice site index sampled from what appears to be the extremes on the ground for any given area is usually all that is needed.

Site indexes for lodgepole pine from environmental factors have not been developed for other areas in the central Rocky Mountains.

Productivity indexes for lodgepole pine based on vegetation, soils, or landform, or a combination of these factors have been developed in Canada and the Pacific Northwest by Duffy (1964), Illingworth and Arlidge (1960), Stanek (1966), Youngberg and Dahms (1970) and others, but productivity in relation to these factors has not been investigated in the central Rocky Mountains.

GROWTH AND YIELD

Forest management in the lodgepole pine type in the central Rocky Mountains is in a period of transition from unmanaged to managed stands. Management is based on silvicultural control over (1) growth and development of individual trees and (2) growth and yield of stands for different products. The most powerful silvicultural control available to the manager is the manipulation of the amount and distribution of growing stock by thinnings and other intermediate cuttings.

Growth of Immature Stands

NUMBER OF STEMS

Lodgepole pine often reproduces so abundantly following fire or clearcutting that competition for growing space does not permit good development (fig. 26). Although shade-intolerant, lodgepole pine does not thin well naturally, and severe crowding of young trees of the same size leads to stagnation of growth. In Colorado, for example, 10 small plots established in a young stand after fire supported an average of 44,000 trees per acre (Mason 1915a). In Montana on burned areas, there were as many as 300,000 1-year-old seedlings per acre, and up to 175,000 8-year-old trees per acre (Tackle 1961a). Initial stocking largely governs reduction in number of stems per acre in natural stands as development progresses. In one study, very heavy mortality (10,200 stems per acre) occurred in a 35-year-old stand over a 20-year period (Alexander 1960). Even with fewer stems per acre and crown classes well differentiated, however, too many trees persist to make good use of available growing space, and artificial thinning is needed to concentrate growth on fewer stems.

Lodgepole pine stands are also characterized by extreme variation in number of trees per acre. Variations in stocking are associated more with such factors as differences in fire intensity and seedbed condition, previous age and stand density, and available seed supply than with site quality (Smithers 1961). Dense stands remain dense regardless of site quality.

Thinning generally reduces mortality in proportion to the number of stems removed (Alexander 1960, 1965; Barrett 1961). Mortality in thinned stands is little affected by age or initial size.

DIAMETER

Because of its response to changes in stand density, diameter growth is usually used in thinning studies to measure release. Diameter growth of lodgepole pine is usually considered slow, but slow growth is due largely to overcrowding.

Most thinning studies show that diameter growth is greatest at the lowest density and slowest at the highest density (Alexander 1956b, 1960, 1965; Barrett 1961; Dahms 1967, 1971a, 1971b; Smithers 1957, 1961). This relationship holds whether all trees or the largest 100, 200, 300, and so forth, trees per acre are compared. In contrast, Daniel and Barnes (1959) reported that, when stand density was 2,500 stems per

Figure 26.—Dense 60-year-old stand of second-growth lodgepole pine. Medicine Bow National Forest, Wyoming.

acre or less, the diameter growth of the 400 largest trees per acre was only moderately improved by heavy thinning. Furthermore, average diameter of the 400 largest trees decreased more rapidly than for all trees as stand density increased above 2,500 stems per acre.

In central Oregon, diameter growth was poorly correlated with initial diameter (Dahms 1971a, 1971b). Alexander (1960) found, however, that for comparable stand density in the central Rocky Mountains, the larger the initial diameter the larger the average stand diameter at any periodic interval after thinning. He also found in an earlier study (Alexander 1958c) that average diameter growth per tree in stands 30 to 80 years old was greater in younger than older stands at any stocking level from 200 to 20,000 stems per acre (fig. 27). In all stands examined over long periods of time, there was a tendency for diameter growth to slow with increasing age (Alexander 1960, Dahms 1971b).

The effects of stand density on diameter growth are well documented, but there is little information on the effect of site quality on diameter growth. Smithers (1957) suggested that the diameter growth of the 200 largest trees per acre was more rapid on good than poor sites in stands of comparable density over a range of ages. Myers' (1966) yield tables for managed stands indicate a similar relationship between diameter growth and site quality.

HEIGHT

The response of height growth to thinning has been variable. In Colorado and Wyoming, no consistent relationship was found between the height growth of either all trees or the 100 largest trees per acre and age, average stand diameter, or stand density (Alexander 1960, 1965). On some plots, height growth was greater in thinned than unthinned stands, in others the reverse was true, and in still others there were no differences. In central Oregon, the height growth of all trees and 100 largest trees per acre was increased by reducing stand density, but the differences between levels of stocking were slight (Barrett 1961, Dahms 1967, 1971b). In Montana, the height growth of dominant and codominant trees was greater than for intermediate and suppressed trees within treatments, but there was no difference in height growth between treatments for comparable crown classes (Lotan 1967b).

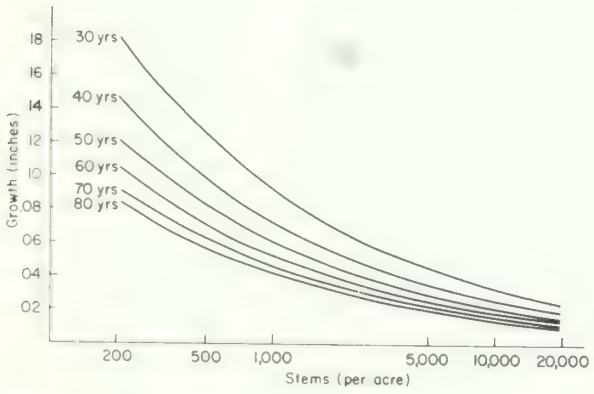

Figure 27.—Relationship of average annual diameter growth per tree to age and number of stems per acre.

In unthinned stands, the effect of stand density on height growth has been well documented (Holmes and Tackle 1962, Smithers 1956, 1957). For that reason the dominant height of lodgepole pine does not constitute a valid site index unless it is adjusted for any reduction due to stand density (Alexander 1966c, Alexander et al. 1967). The changes in dominant height of lodgepole pine with age and site quality are shown in figure 25 for the range of stand density — measured as CCF — where height growth is unaffected. At age 50 years, for example, dominant height varies from 20 to 64 ft in response to variations in site quality. At CCF 300, the dominant height of trees in a 50-year-old stand varies from 16 to 50 ft (Alexander 1966c). Here the response to changes in site quality are confounded by stand density. Without the adjustment in site index, the estimate of site quality would not be valid.

BASAL AREA

Most thinning studies have shown that total basal area growth per acre is related to stand density. The greater the initial basal area or number of stems the greater the basal area at any periodic interval (Alexander 1960, 1965; Dahms 1971a, 1971b). These studies also show that basal area increment per acre decreases with increasing age, but there is less agreement on the rate of basal area increment in relation to stand density. In a study in the central Rocky Mountains, basal area increment in stands averaging 1 inch in diameter increased with an increase in number of stems up to 1,200 per acre, while in stands where the average d.b.h. was 5 inches, basal area increment decreased when the number of stems per acre increased above 300 or when basal area per acre was about 80 ft^2 (Alexander 1960). In another study on the Fraser Experimental Forest in Colorado, there were no differences in basal area increment between thinned and unthinned stands despite drastic reductions in stand density (Alexander 1956b, 1965). Elsewhere, Barrett (1961), Dahms

(1971a, 1971b), and Daniel and Barnes (1959) reported that basal area increment increased with an increase in basal area per acre.

VOLUME

Volume per acre is the ultimate objective of yield prediction; in young stands ft^3 volume is of most interest. Thinning studies in Colorado show that total ft^3 volume per acre increases with an increase in stand density (Alexander 1965), but in Oregon and Alberta, an increase in the number of stems reduced total ft^3 volume in densely stocked stands (Dahms 1971b, Smithers 1956). There is also disagreement on the relationship of total ft^3 volume increment to stand density. In some studies, thinning resulted in a temporary reduction in total ft^3 volume increment (Alexander 1965, Dahms 1971a). Thereafter, total ft^3 increments of thinned and unthinned stands were comparable. In other studies, total ft^3 volume increment increased with an increase in stand density measured as either basal area or CCF (Dahms 1966, 1967). In most studies, however, net total ft^3 volume was greater in thinned than unthinned stands except at very low densities. Furthermore, regardless of whether thinning increased total ft^3 volume increment, growth on thinned plots was concentrated on fewer, larger, and more usable stems (Alexander 1965; Dahms 1967, 1971b).

Crown Size

Under stand conditions, the crowns of lodgepole pine tend to be conical. The relationship of crown size to individual tree growth has been determined for open-grown trees in the Rocky Mountains (Alexander et al. 1967). Figure 28 shows the relationship of the crown width of open-grown pines to diameter at breast height for the central Rocky Mountains, Intermountain area, Pacific Northwest, and the three areas combined. Dahms (1971b) investigated the effect of stand density on crown length and width in thinned young stands. He found that 10 years after thinning, crowns were wider and longer for trees of comparable diameters at the lowest stand densities observed.

Volume Tables

Volume tables and point sampling factors have been prepared for lodgepole pine in Colorado (Myers 1964, 1969). These tables include:

1. Gross volumes in total and merchantable ft^3.
2. Gross volumes in fbm, both Scribner and International ¼-inch log rules.
3. Point sampling factors for merchantable ft^3 and fbm.

Volume per unit of area may be determined from either:

1. Measurements of tree diameters and heights,
2. Measurements of diameters and sufficient heights to convert tables to local volume tables, or
3. Tree counts obtained by point sampling.

Yields of Unmanaged Old-Growth Stands

Although the proportion of lodgepole pine stands still in old-growth is not as high as in

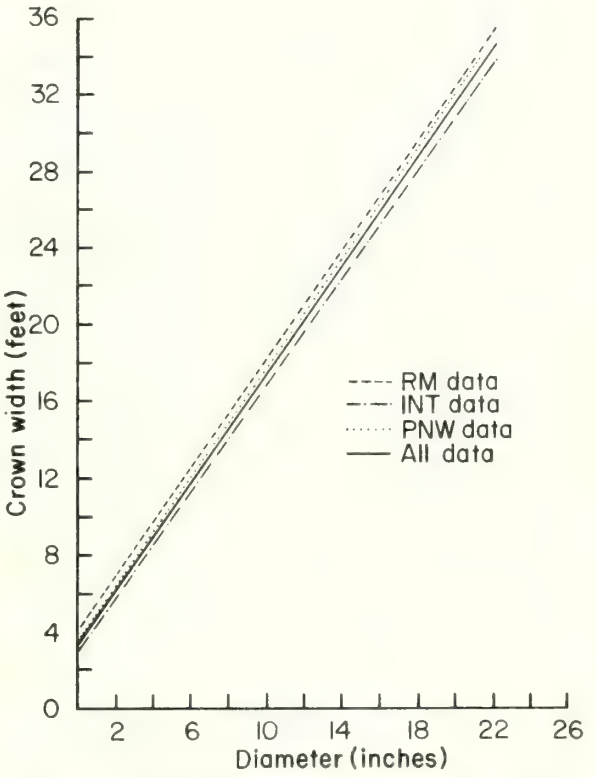

Figure 28.—Relationship of crown width to stem diameter at breast height for open-grown lodgepole pines. (RM = Rocky Mountain; INT = Intermountain; PNW = Pacific Northwest.)

spruce-fir forests, many of the poletimber-sized stands are also overmature. The manager, therefore, must largely accept what nature has provided during the period of conversion to managed stands. Forest Survey data indicate that average annual growth over all sites in old-growth lodgepole pine is about 25 to 40 fbm per acre. This low productivity is largely due to the great number of small trees.

Average volumes per acre in unmanaged old-growth stands in the Rocky Mountains depend on both density and environment. For example, in a 100-year-old stand, maximum volume was 20,000 fbm with 800 stems per acre, and only 1,500 fbm with 1,800 stems per acre (Tackle 1961a). In Colorado and Wyoming, yields of 12,000 to 15,000 fbm per acre are generally considered good; yields of 20,000 to 25,000 fbm per acre are exceptional (Thompson 1929).

Thinning studies have shown that, by reducing stand density at a young age, it is possible to obtain production comparable to ponderosa pine in the Black Hills — net annual increment of 150 fbm per acre on average sites — and distribute this growth over fewer and larger stems.

Yields of Managed Stands

Old-growth lodgepole pine sawtimber- and poletimber-sized stands are being converted into stands that must be managed from the regeneration period to final harvest. Furthermore, there are many stands of young growth that must be brought under management. Some of these stands have been thinned once but are in need of a second thinning.

Yield tables for managed stands are the basis for timber management planning. They report probable wood yields that will result from specified combinations of such factors as site quality, utilization standards, and frequency and intensity of thinning. They also provide an important part of the information needed for determining the influence of timber treatments on all forest resources. Yield tables for lodgepole pine are useful regardless of the current level of management. Well-managed forests can benefit from refinements in operations that are guided by comparisons of actual conditions with a good standard. Where conversion to managed stands is underway, yield tables provide goals toward which conversion can be directed. Furthermore, a manager should not be restricted to only one yield table per working group or series of stands managed under the same silvicultural system. He must have the opportunity to examine the probable results of his operations, to make necessary changes in the management of any of his resources, and to study the effects of these changes before money is spent on them (Myers 1967).

Field and computer procedures for preparing yield tables for managed stands, including those infected with dwarf mistletoe, realistically simulate (1) stand growth, (2) response to thinning, and (3) reproduction cutting by any of the even-aged systems (Myers, 1967, 1971; Myers et al. 1971). These procedures were developed from field data on past growth in relation to stand density, age, and site quality obtained from a large number of temporary plots in existing thinned stands of lodgepole pine.

To use the procedures in stands ready for final harvest and conversion to managed stands, the manager must decide on (1) the regeneration system — clearcutting, group selection or shelterwood — with natural or artificial regeneration, (2) the site index, (3) initial stocking (between 1,500 and 2,000 stems per acre at age 10 years are recommended because lodgepole pine requires some crowding at early ages to obtain height growth) and (4) age of initial thinning. He can then use the computer simulation program to produce a series of yield tables for different combinations of growing stock levels, cutting cycles, and rotation ages that will show how project outcomes will vary in response to different cultural treatments. The manager can then examine the probable results of different courses of action, and select the one that best meets his particular management goals.

To use the procedures to put existing stands not yet ready for final harvest under management, the manager must develop the necessary working tools from information obtained on age, diameter, height, site quality, stand density, and past growth. He can then use the computer simulation program to produce a series of yield tables for different combinations of growing stock levels, cutting cycles, and rotation ages that will show how project outcomes will vary with intermediate cutting treatments and past site and stand conditions. The manager can then select the one that best meets his management goals.

Cole (1971) has developed a stand volume equation for even-aged stands of lodgepole pine in Montana and Idaho that gives direct estimates of gross total ft^3 volumes from measurements of stand basal area and the height of dominant trees, and provides conversion factors to estimate merchantable ft^3 volumes. This equation should be substituted when Myers' (1967, 1971) computer simulation program is used to estimate yields of managed stands of lodgepole pine in the northern Rocky Mountains.

SILVICULTURE AND MANAGEMENT OF OLD GROWTH

Regeneration Silviculture

Harvest-cutting methods applicable to old-growth lodgepole pine forests include clearcutting, and shelterwood and group selection cuts. Seed-tree and individual-tree selection cutting are usually not applicable. The objective of each regeneration system is to harvest the timber crop and obtain adequate reproduction. The choice of cutting method in lodgepole pine stands depends upon management goals, but stand conditions, windfall, disease and insect susceptibility, and the risk of potential fire damage that vary from place to place on any area limit the options available for handling individual stands. Furthermore, the economics of harvesting, manufacturing, and marketing wood products from a large number of small diameter trees in the central Rocky Mountains further limits cutting practices. Cutting to bring old-growth lodgepole pine under management is likely to be a compromise between what is desirable and what is possible. Management on many areas may involve a combination of clearcutting small areas, several partial cutting treatments, and no cutting.

CLEARCUT AREAS

Clearcutting is a regeneration system that harvests the timber crop in one step. Forest managers concerned with timber production have most often elected to convert lodgepole pine to managed stands by clearcutting in strips, patches, or blocks. There are several reasons for this: (1) Lodgepole pine, a pioneer species, is shade-intolerant and reproduces best in most instances when overstory competition is removed or drastically reduced. (2) Dwarf mistletoe — present in many stands in varying degrees — is best controlled by separating the old stand from the new. (3) Windfall and mountain pine beetles, while variable, are always a threat. (4) The potential for future growth is limited because of the generally low vigor of mature and overmature stands and the suppressed condition of many smaller trees. Furthermore, many natural stands appear to be even-aged, having developed after catastrophic fires or other disturbances.

Harvesting and regeneration practices developed in the Rocky Mountains have been directed toward clearcutting. Much of the criticism directed at clearcutting in general has been associated with concern about (1) the large openings cut, (2) geometric patterns that did not complement the landscape, (3) logging slash and unmerchantable debris left on the ground, (4) failure of areas to regenerate, and (5) the unknown effect of roadbuilding and logging on other forest resources. In some cases the objections are valid, but with some critics, clearcutting has unjustifiably become synonymous with devastation.[17]

From a silvicultural point of view, clearcutting is still an acceptable harvesting method in lodgepole pine where timber production is a major objective, providing the knowledge available is put into practice. Under some conditions clearcutting is the only alternative to no cutting. Furthermore, a combination of cleared openings and high forest is desirable for increasing water yields and improving wildlife habitat. The following section will therefore consider the practices needed to regenerate clearcut areas with natural or artificial regeneration.

Management with Advanced Regeneration

There is seldom a manageable stand of advanced regeneration under pure lodgepole pine, or if present it has been suppressed for so long that it has no future management potential. In mixed stands, where the associated species are spruce and fir, there is frequently a stand of advanced reproduction. Procedures developed for spruce-fir stands should be followed to (1) evaluate the potential for management before logging, (2) set up cutting and slash disposal controls necessary to save the advanced reproduction if the manager decides to use it, and (3) evaluate the adequacy of stocking and need for fill-in reproduction after logging (Roe et al. 1970).

Management with Reproduction Following Cutting

Most lodgepole pine areas will be regenerated with either natural or artificial reproduction after logging. Cutting unit layout, logging plans, and slash disposal and seedbed treatment should be designed to (1) facilitate seed dispersal, (2) promote seedling survival and establishment, and (3) create favorable growing conditions. If natural regeneration fails, plans should be made to use artificial regeneration.

[17] *Lotan, James E. The clearcutting controversy and management of lodgepole pine. (Manuscript in preparation at Intermt. For. and Range Exp. Stn., Ogden, Utah.)*

Clearcutting can be by patches, blocks, or strips. Those cutting practices can be readily adapted to multiple-use land management by judicious selection of size, shape, and arrangement of openings in combinations with other high-forest cutting practices.

Size of Opening.—Successful natural regeneration in lodgepole pine depends upon an adequate supply of seed falling on a receptive seedbed. In the central Rocky Mountains there are no data on seed-to-seedling ratios, but Lotan (1964a) estimated that from 30 to 50 sound seeds would be required to produce one first-year seedling on mineral soil seedbeds with abundant moisture and favorable temperatures. Assuming that an arbitrary minimum of 1,500 first-year seedlings are sufficient to allow for normal mortality and still provide the density necessary to obtain early height growth, between 45,000 and 75,000 sound seeds per acre will be needed before the seed supply can be considered adequate.

The size of opening that is likely to receive sufficient seed to restock receptive seedbeds is influenced by whether the seed is dispersed by open or closed cones. The manager cannot assume that the cone habit is either serotinous or nonserotinous. He must examine each area and classify the stand as (1) closed cone, (2) open cone, or (3) intermediate. If the stand is classified as closed cone, the manager must then determine if he has sufficient sound seed stored in closed cones to provide an adequate seed source for natural regeneration, using the procedures developed by Lotan and Jensen (1970).

1. *Stands with Serotinous Cone Habit.*—The size and shape of openings cut in these stands that will restock is highly flexible if there is an adequate supply of seed. Natural regeneration is a one-shot opportunity, however, because the seed supply is in the slash-borne cones. There is no advantage to cutting openings larger than 30 to 40 acres, even for dwarf mistletoe control,[17] and openings 10 to 20 acres would be more compatible with other uses. On south slopes and other difficult regeneration chances, it may be desirable to cut openings smaller than 10 acres to provide a supplemental seed source in trees standing around the perimeter. If there is not an adequate supply of seed in closed cones, follow the recommendations below.

2. *Stands with Nonserotinous or Intermediate Cone Habit.*—The cutting unit must be designed so that seed from the surrounding timber margin reaches all parts of the opening unless artificial regeneration is planned. Effective seed dispersal distance from standing trees has not been studied in the central Rocky Mountains, but studies elsewhere (Boe 1956, Dahms 1963, Tackle 1964) indicate that, with favorable seedbed and environmental conditions, the effective seeding distance in lodgepole pine is about 150 ft. The maximum width of opening likely to restock to natural reproduction is therefore 300 ft, or about four to five times tree height. Furthermore, it is not likely that sufficient seedfall to provide adequate stocking will be obtained from only one seed crop. On south slopes openings should be smaller — 150 ft wide or about two to three times tree height. If larger openings are cut, plan on planting the area beyond effective seeding distance.

Windfall.—Windfirmness must be a significant consideration in the location of cutting boundaries, especially in stands with nonserotinous cones. Guidelines for minimizing windfall around the perimeters of clearcut openings in spruce-fir forests (Alexander 1964, 1967b) should also be used when locating boundaries for lodgepole pine clearcuts.

Seedbed Preparation and Slash Disposal.—There are a number of things to consider in planning the treatment of lodgepole pine slash: (1) in stands with serotinous cones, careful handling of slash is required to avoid destruction of seed-bearing cones, (2) heavy concentrations of slash obstruct seedling establishment and are a fire hazard, and (3) slash creates an adverse visual impact.

1. *Stands with Serotinous Cone Habit.*—Dozer piling or windrowing dry slash over the entire area has usually resulted in overly dense stands of reproduction because abundant seed is shaken out of cones onto exposed mineral soil seedbeds (Alexander 1966a, Boe 1956, Tackle 1964). Dozer piling and windrowing slash, then burning the concentrated slash, has frequently resulted in poor stocking, especially when the slash fires burned over much of the area and destroyed most of the seed. Broadcast burning usually results in little or no restocking because most of the seed is destroyed. Disposal of slash by lopping and scattering, and by rolling and chopping have resulted in adequate restocking if sufficient mineral soil (about 40 percent of the area) has been exposed and the seed-bearing cones are placed near the ground. Fire hazards and visual impact are usually not reduced sufficiently, however.

Concentrations of slash must be treated. If these concentrations are piled or windrowed for burning, the piles and windrows must be kept small (1/20 acre or less) and well distributed so that the burned area does not occupy more than 25 percent of the total area. The lighter areas of slash — less than 40 percent of the area covered with slash less than 1 ft deep — can be either lopped and scattered or rolled and chopped. This combination of treatments will reduce fire hazards and visual impact, provide exposed mineral soil, scatter the cone-bearing slash over the area, and place the cones near or on the ground.

2. *Stands with Nonserotinous or Intermediate Cone Habit.*—Slash can be handled in the same way as in stands with serotinous cones, or it can be broadcast burned. If slash is piled or windrowed for burning, the piles should be kept small and well distributed because burning in large concentrations often heats the soil enough to inhibit subsequent plant growth. To be effective, broadcast burning should cover about 75 percent of the area. It should consume most, but not necessarily all, of the logging slash, other debris, and duff or organic material on the ground, and it should burn hot enough to destroy most of the competing vegetation. It should not burn so hot, however, that a deep layer of loose ash accumulates. Areas with light slash can be lopped and scattered or rolled and chopped. It may be necessary to do some additional mechanical scarification on lopped and scattered areas. Tractors with brush blades should be used, and about 40 percent of the area should be left with exposed mineral soil.

Management for Artificial Regeneration

Planting.—Guidelines for planting lodgepole pine are not available in the central Rocky Mountains, but many of the recommendations for spruce planting prepared by Ronco (1972) are applicable to lodgepole pine.

1. *Need and Timing.*—Sites scheduled for planting should be reforested immediately after logging and slash disposal. Areas prepared for natural reproduction that fail to restock in 3 years should be planted, otherwise additional seedbed preparation is likely to be needed. A minimum goal should be 1,200 well-established seedlings per acre where timber production is a primary objective. If the manager intends only to hold the site, a minimum of 600 seedlings per acre is sufficient.

2. *Site Preparation.*—Planting will ordinarily require just as much seedbed preparation as natural seeding. Exceptions are areas where slash has been broadcast burned or completely cleaned up by dozer piling or windrowing and burning within 3 years of planting. However, burned areas with deep layers of loose ash will require ground preparation. Hand site preparation will probably be adequate on small planting jobs and for fill-in planting. Hand-scalped spots should not be smaller than about 18 to 24 inches square. Aboveground parts of competing vegetation should be totally removed. On large areas, or where hand scalping is unsatisfactory because of dense grass or herbaceous vegetation, mechanical site preparation should be used. Machine methods include disking, plowing (furrowing, mounding, and ridging), and dozing. Complete scarification is not necessary, but vegetation-free areas should be about 2 ft wide and lie on the contour. Where competing vegetation consists of brush, tractors equipped with angle dozer blades should be used to either completely clear the area or remove the brush in strips the width of the dozer blade.

3. *Planting Stock.*—Plant only stock that meets the following specifications: (1) stem caliper, ⅛ inch, (2) tops no shorter than 3 inches, (3) roots at least 9 inches long, and (4) top-root ratio no more than 3 to 1.

4. *Planting Season.*—Lodgepole pine should be planted in the spring after snowmelt. Planting should be completed by June 25. Temporarily suspend planting during the regular season when temperatures are unseasonably warm, especially on clear days when the wind is blowing.

5. *Storage.*—Lodgepole pine planting stock must be lifted while seedlings are still dormant, and stored at the nursery until the planting sites are free of snow. Storage should not be extended for longer than 3 months. During transit from nursery to planting site, the seedlings must be treated as dormant plants. If refrigerated transport is not available, the bundles or bags should be covered with canvas to protect them from the sun and wind. Temperatures should be maintained between 34° and 40° F. Packages should be arranged to provide air circulation under the covering. Water trees in bundles before loading. Storage problems are more

severe in the field because limited facilities on the planting site make temperature control difficult. Well-insulated storage sheds that can be cooled by ice or snow can be used in the absence of mechanical refrigeration. Trees in bundles should be kept moist and care taken not to lower temperatures below freezing. If storage sheds are not available, cool, moist cellars or snowbanks can be used. Seedlings can be held in local storage up to 7 days if temperatures can be maintained below 40° F. Otherwise, local storage should be limited to 3 days. When transferring trees from bundles or bags to planting containers, handle the seedlings carefully to prevent breakage and keep the roots covered with moist spaghnum moss.

6. *Spot Selection.*—Plant seedlings in moist mineral soil. On areas that have been hand scalped, seedlings should be planted to take advantage of dead shade wherever possible. The north and east side of stumps, logs, and rocks are favorable locations. Avoid planting in deep layers of loose ash, adjacent to shrubs or other live vegetation that competes for soil moisture, near cut banks and under logs where sloughing action can injure or kill seedlings, and trails or stock concentration areas where trampling damage may occur. Choice of planting spot is less critical on areas that have been plowed or stripped; there is little opportunity for individual spot selection when using tree-planting machines.

7. *Planting Method.*—Use the hole method for hand planting. Dig holes with mattock hand tools or power augers. If augers are used, do not dig holes too far in advance of planting or they will dry out.

8. *Plantation Protection.*—New plantations should be protected from trampling damage by livestock until seedlings are at least 3 ft high. This will require fencing or other adjustments in grazing allotments. New plantings should also be protected from rodents. Sample the rodent population on the areas to be planted. If populations are large, provide controls until seedlings become established.

9. *Records.*—Adequate data from detailed records are needed to (1) correct deficiencies causing failure, and (2) recognize good practices leading to successful plantations. Decisions affecting regeneration practices can then be based on quantitative information rather than conjecture. Follow the recommendations suggested by Ronco (1972).

Seeding.—Techniques have not been worked out in the central Rocky Mountains, but direct seeding of lodgepole pine on prepared seed spots has been successful in the northern Rocky Mountain and Intermountain regions. In a study in an *Abies lasiocarpa-Vaccinium scoparium* habitat type in northwestern Wyoming, 12 seeds (90 percent viable) were sown in June on hand-prepared seed spots and covered with ⅛ inch of soil (Lotan and Dahlgreen 1971). Rodents were controlled by poison baits. After 3 years, viable seed-to-seedling ratios were 5:1 on scalped 12-inch-square spots on the level and along the slope; 12:1 on scalped 5-inch-square spots along the slope; and 60:1 for seed sown in the ash and duff left by broadcast burning of logging slash. The percentages of stocked spots were: 72 percent for scalped 12-inch squares on the level; 64 percent for scalped 12-inch squares on the slope; 38 percent for scalped 5-inch squares; and only 10 percent for ash-duff seedbeds.

Roe and Boe (1952) and Tackle (1961b) also successfully spot seeded lodgepole pine on scalped 6- to 12-inch areas in central Montana. Seed-to-seedling ratios were about 5:1 for 10-year-old seedlings.

Spot seeding usually results in better success than broadcast seeding because the seed is placed in a more favorable environment and covered with soil (Lotan and Dahlgreen 1971).

PARTIAL CUT AREAS

Shelterwood and group-selection cutting and their modifications can be used in old-growth lodgepole pine. These regeneration systems harvest the timber on an area in more than one step. From a silvicultural point of view they are the only acceptable options open to the manager where (1) multiple-use considerations preclude clearcutting, (2) combinations of cleared openings and high forest are required to meet the needs of various forest uses, or (3) areas are difficult to regenerate after clearcutting. However, windfall, insects, diseases, and stand conditions impose limitations on how stands can be handled. A careful appraisal of the capabilities and limitations of each stand is necessary to determine cutting practices. Furthermore, partial cutting requires careful marking of individual trees or groups of trees to be removed, and close supervision of logging. The following recommendations are for partial cutting practices keyed to broad stand descriptions, windfall risk situations, and disease and insect problems (Alexander 1972). Practices needed to ob-

tain natural reproduction are also discussed. Stands are pure pine unless otherwise indicated.[18]

Single-Storied Stands[19]

Description.—

1. Stands may appear to be even-aged (fig. 29), but often contain more than one age class, occasionally may even be broad-aged.
2. Codominants form the general level of the canopy, but the difference in height between dominants, codominants, and intermediates is not as great as in spruce-fir stands.
3. If even-aged in appearance:
   a. There is a small range in diameter class and crown length.
   b. Live crown length of dominants and codominants is generally short to medium (30 to 60 percent of the total tree height and boles are generally clear for 10 to 40 percent of total tree height).
   c. There are few coarse-limbed trees in the stand.
4. With two or more age classes, the younger trees usually have finer branches, smaller diameter, longer live crown, and less clear bole than older trees.
5. Stocking is generally uniform.
6. A manageable stand of advanced reproduction is usually absent.
7. In **mixed stands,** the overstory is either (a) pure pine or(b) pine and Engelmann spruce, subalpine fir, or Douglas-fir, with advanced reproduction of species other than pine that may or may not be a manageable stand.

Recommended Cutting Treatments.—

Single-storied stands are usually the least windfirm because trees have developed together over long periods of time and mutually protect each other from the wind.

1. **Low windfall risk situations—**

The first cut can remove about 30 percent of the basal area on an individual tree basis. This initial entry is a **preparatory cut** that resembles the first step of a three-cut shelterwood, since it probably does not open up the stand enough for pine reproduction to become established in significant numbers. Overstory trees are all about equally susceptible to blowdown, therefore the general level of the canopy should be maintained by removing some trees in each overstory crown class. The cut should come from C and D vigor class trees, but openings larger than one tree height in diameter should be avoided by distributing the cut over the entire area. Do not remove dominant trees that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut. In **mixed stands,** if the overstory is pure pine, handle as a pure stand; if the overstory is of mixed composition, cut as much of the basal area recommended in pine as is possible to release the climax species.

The second entry into the stand should not be made until 5 to 10 years after the first cut to permit the stand to develop windfirmness.

[18] *In a mixed stand, either less than 80 percent of the overstory basal area is lodgepole pine, or the overstory is pine with an understory of a different species.*

[19] *Reproduction less than 4.5 ft tall is not considered a stand story in these descriptions.*

SINGLE-STORY

Figure 29.—A single-storied lodgepole pine stand.

The second cut should also remove about 30 percent of the original basal area on an individual tree basis. It simulates the second or **seed cut** of a three-step shelterwood. The largest and most vigorous dominants and codominants should be reserved as a seed source in stands with the nonserotinous or intermediate cone habit, but avoid cutting openings in the canopy larger than one tree height in diameter by distributing the cut over the entire area even if it means leaving trees in the C and D vigor classes with poor seed production potential. In **mixed stands** cut as much of the recommended basal area in pine as is possible without creating openings larger than one tree height. The last entry is the **final harvest** and should remove all of the remaining original overstory. It should not be made until a manageable stand of reproduction has become established, but the cut should not be delayed beyond this point if timber production is the primary concern because the overwood (1) hampers the later growth of seedlings, and (2) if infected with dwarf mistletoe, will reinfect the new stand (fig. 30).

The manager also has the option of removing less than 30 percent of the basal area at any entry and making more entries, but they cannot be made at more frequent intervals. The cut will be spread out and continuous high forest cover maintained for a longer period of time. This option is not recommended where mountain pine beetles and dwarf mistletoe impose limitations on how stands can be handled.

The usual uniform arrangement of individual trees in single-storied stands is not well adapted to removing trees by **group-selection cutting.** Occasionally, however, natural openings do occur when stands begin to break up. Also, small openings may be desirable to meet management objectives. An alternative to removing trees on an individual basis would be to remove about 30 percent of the basal area in groups. Openings should be kept small, not more than one to two times tree height in diameter; not more than one-third of the area should be cut over at any one time. **This kind of cutting should be used only in stands where insect and disease problems are minimal.**

The second entry into the stand should not be made until the first openings have been regenerated. This cut should also remove about 30 percent of the original basal area without cutting over more than an additional one-third of the area. Openings should be no closer than about one to two tree heights to the original openings.

The final entry should remove the remaining groups of merchantable trees. The timing of this cut depends upon the cone habit and how the manager elects to regenerate the openings. If he chooses to use natural regeneration and the stand is classified as nonserotinous or intermediate cone habit, the final harvest must be delayed until the trees in the original openings are large enough to provide a seed source.

The manager may choose to remove less than 30 percent of the basal area and cut over less than one-third of the area at any one time. This will require more entries, but each new cut should not be made until the openings cut the previous entry have regenerated. Furthermore, in stands with nonserotinous or intermediate cone habit, the last groups cannot be cut until there is either an outside seed source or the manager elects to plant these openings.

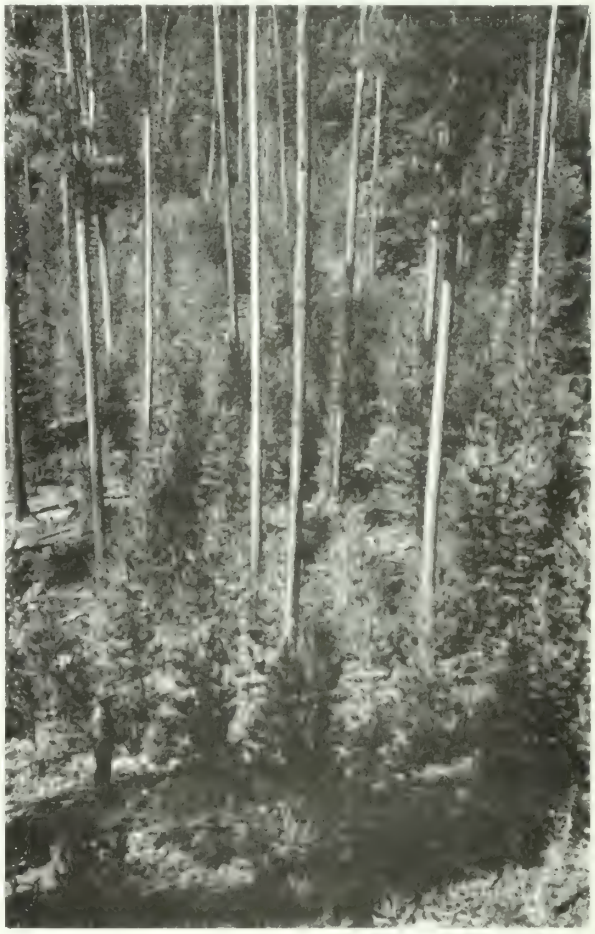

Figure 30.—New reproduction established after the seed cut of a shelterwood system in lodgepole pine. Overwood should have been removed earlier to release the reproduction. Fraser Experimental Forest, Colorado.

2. **Moderate windfall risk situations—**

The first cut should be limited to a light **preparatory** cutting that removes about 20 percent of the basal area on an individual-tree basis. The objective is to open up the stand, but at the same time minimize the windfall risk to the remaining trees. Provision should be made, however, to salvage blowdowns. This type of cutting resembles a **sanitation cut** in that the lowest vigor and poorest risk trees should be removed, but it is important that the general level of the overstory canopy be maintained intact. **Mixed stands** should be handled the same as in low windfall risk situations, except that less basal area should be removed.

The second entry can be made in about 10 years after the first cut. This entry should remove about 20 percent of the original basal area on an individual-tree basis. Windfalls that were salvaged after the first cut should be included in the computation of the basal area to be removed. The objective of this **preparatory cut** is to continue to develop windfirmness while preparing the stand for the seed cut. Most of the trees marked for removal should come from the smaller crown and poorer vigor classes, but maintain the general level of the canopy intact. In **mixed stands** cut as much of the recommended basal area to be removed in pine as is possible.

It will require about another 10 years to determine if the stand is windfirm enough to make another entry. This will be the **seed cut,** and should remove about 20 percent of the original basal area including any windfalls since the last cutting. The largest and most vigorous dominants and codominants in **mixed stands** and pure stands with nonserotinous or intermediate cone habit should be reserved as a seed source, but it is more important to distribute the cut over the entire area.

The last entry is the final harvest, which should remove the remaining original overstory. It cannot be made until a manageable stand of reproduction has been established. About 40 percent of the original basal area will be removed in this cut, and if it is too heavy (10,000 fbm or more per acre) to be removed in one harvest without undue damage to the reproduction, the manager must plan on a final harvest in two steps. The second step can begin as soon as skidding is finished in the first step, if a manageable stand of reproduction still exists.

The manager also has the option of removing less than 20 percent of the basal area at any entry and making more entries, but they cannot be made at more frequent intervals.

3. **High windfall risk situations—**

The choice is limited to removing all trees or leaving the stand uncut. Cleared openings can be up to about 5 acres, interspersed with uncut areas. Cutover areas should not exceed about one third of the total in this risk situation.

Two-Storied Stands

Description.—

1. Stands may appear to be two-aged (fig. 31), but can contain more than two age classes.
2. Top story — dominants, codominants, and intermediates — resembles a single-storied stand.
3. Second story is composed of younger trees of smaller diameter — small saw logs, poles, or saplings — than the top story, but it is always

Figure 31.—A two-storied lodgepole pine stand.

below and clearly distinguishable from the overstory. Trees in the second story are overtopped and may or may not be suppressed.
4. If more than two-aged, the overstory usually contains at least two age classes. The younger trees are finer limbed and may be smaller in diameter than the older trees. The second story may also contain more than one age class.
5. Stocking of the overstory may be irregular, but overall stocking is usually uniform.
6. A manageable stand of advanced reproduction is usually absent.
7. In **mixed stands,** the overstory is usually pure pine, but occasionally it may be pine with spruce or Douglas-fir. The second story is usually spruce and fir at the higher elevations, and Douglas-fir at the lower elevations.
8. Stocking in **mixed stands** may vary from uniform to irregular.
9. **Mixed stands** may have a manageable stand of advanced reproduction of species other than pine.

Recommended Cutting Treatments.—Same as for three-storied stands.

Three-Storied Stands

Description.—

1. Stands may appear to be three-aged (fig. 32), but they can contain more than three age classes, although stands are seldom broad-aged.
2. Top story resembles a single-storied stand except that there are fewer trees.
3. The second and third stories consist of younger, smaller diameter trees. Second story may be small saw logs or large poles, while the third story is likely to be composed of small poles or saplings. Second and third stories are overtopped, and some trees may be suppressed.
4. Overall stocking is likely to be uniform, but stocking of any story may be irregular.
5. A manageable stand of advanced reproduction is usually absent.
6. In **mixed stands** the top story may be either pure pine or a mixture of pine and other species. The second story is usually spruce and subalpine fir at the higher elevations, and Douglas-fir at the lower elevations. The second story may occasionally contain some pine, but it is rarely pure pine. The third story is almost always composed of species other than pine.
7. Stocking in **mixed stands** can vary from uniform to irregular.
8. **Mixed stands** often have a manageable stand of advanced reproduction of species other than pine.

Recommended Cutting Treatments (Two- and Three-Storied Stands).—Trees in the top story are usually more windfirm than those in a single-storied stand. Trees in the second and third stories are usually less windfirm than trees in the top story.

1. **Low windfall risk situations—**

The first cut can remove up to 50 percent of the basal area in **two-storied stands** (providing not more than half of the basal area removed comes from the top story), and up to 40 percent of the basal area from **three-storied** stands. This cutting is as heavy as the first or **seed cut** of a two-cut shelterwood, but marking follows the rules for individual-tree selection. Heavier cutting may be possible in three-storied stands, but

THREE–STORY

Figure 32.—A three-storied lodgepole pine stand.

the appearance of a continuous overstory is not likely to be retained. Trees removed should be in vigor classes C and D insofar as possible, but since the top story is likely to be more windfirm, selected dominants and codominants should be left even when they are in vigor classes C and D, if they do not have dead or dying tops. Avoid cutting holes in the canopy larger than one tree height in diameter by distributing the cut over the entire area. Do not remove dominant trees that are protecting other trees to their leeward if these latter trees are to be reserved for the next cut. In **mixed stands,** if the top story or, rarely, the first and second stories are pure pine, handle as a pure stand. If the top story is of mixed composition, cut as much of the basal area to be removed in pine as is possible to release the climax species, but do not cut all of the pine if it is needed to maintain the overstory.

The second entry should be the **final harvest** to remove the remaining original stand and release the reproduction. It cannot be made until the new stand of reproduction is established. If the residual volume is greater than about 10,000 fbm per acre, the final harvest should be made in two steps to avoid undue damage to newly established reproduction. The second step can begin as soon as skidding is finished in the first step, if a manageable stand of reproduction still exists.

If there is a manageable stand of advanced reproduction under **mixed stands,** the first cut can be an **overstory removal** if the volume is not too heavy. Otherwise, the first cut can remove 40 to 50 percent of the basal area on an individual-tree basis as long as the more windfirm dominants and codominants are left. The timing of the second cut is not critical from a regeneration standpoint so long as a manageable stand of reproduction still exists after the first cut and can be saved.

The manager has other options to choose from. He may elect to cut less than the recommended basal area, make more entries, and spread the cut out over a longer period of time by delaying the final harvest until the new stand is tall enough to create the appearance of a high forest. **This is not recommended where mountain pine beetles and dwarf mistletoe limit how stands can be handled.**

In **pure** or **mixed** stands with irregular stocking that may have resulted from the breakup of single-storied stands, old beetle attacks, or windfall losses, an alternative first cut can remove about 40 percent of the basal area in a modified group selection. The group openings can be larger (two to three times tree height) than in single-storied stands, but the area cut over should not exceed about one-third of the total. Openings should be irregular in shape without wind-catching indentations in the borders. This kind of cutting is not applicable in pure stands where mountain pine beetle or dwarf mistletoe impose limitations, because the interval between initial cutting and final harvest is likely to be too long to prevent serious mistletoe infection of new reproduction and/or loss of beetle-susceptible trees.

Two additional entries can be made in the stand. They should each remove about 30 percent of the original basal area in group openings up to two to three times tree height, but not more than one-third of the area should be cut over at any one time. If there is not a manageable stand of advanced reproduction, the manager must wait until the first openings are regenerated before cutting the second series. Furthermore, in **mixed stands,** or **pure** stands with the nonserotinous or intermediate cone habit, he must either delay cutting the final groups until there is a seed source or plan on planting these openings. If there is a manageable stand of advanced reproduction, the timing between cuts is not critical from a regeneration standpoint.

The manager has the option in **mixed stands** of removing less than the recommended basal area and cutting less than the recommended area at any one time. This will require more entries and spread the cut out over a longer period of time.

2. **Moderate windfall risk situations—**

The first entry should be a **preparatory cut** that removes not more than 30 percent of the basal area on an individual-tree basis. Predominants, and codominants and intermediates with long live crowns should be removed first. The remaining cut should then come from trees in vigor classes C and D. Maintain the general level of the canopy by not cutting holes larger than one tree height in diameter in the canopy. Provision should be made to salvage blowdowns. **Mixed stands** should be handled as in low wind risk situations, except that less basal area should be removed.

The second entry should not be made in less than 10 years. This cut should remove about 30 percent of the original basal area, including the salvage of any windfalls after the first cut. The second entry is the **seed cut.**

The best dominants and codominants should be reserved as a seed source in stands with the nonserotinous or intermediate cone habit, but it is important that the cut be distributed over the entire area.

The next entry is the **final harvest** to remove the remaining merchantable volume and release the new reproduction after it has become established. However, if the residual stand has too heavy a volume, the final harvest should be made in two steps.

In **mixed stands** that contain a manageable stand of reproduction, and if the volume per acre is not too heavy, the first cut can be an **overwood removal.** If the volume is too heavy for a one-step removal, the manager should follow the recommendations for pure stands because the wind hazard is too great to permit a two-step removal in a stand that has not been previously opened up to develop windfirmness.

3. **High windfall risk situations—**

The choice is limited to either removing all the trees or leaving the stand uncut. Cleared openings can be up to about 5 acres, interspersed with uncut areas. The cutover area should not exceed about one-third of the total in this risk situation.

Multi-Storied Stands

Description.—

1. Stand is usually broad-aged (fig. 33) with a wide range in diameters.
2. If stands developed from relatively few individuals following disturbance, the overstory trees are coarse limbed. Fill-in trees are better formed and finer limbed. Vigor of the overstory trees varies from poor to good.
3. In stands that developed from deterioration of single- or two-storied stands, the overstory trees may be no limbier than the fill-in trees. Nearly all of the healthy, faster growing trees are below saw-log size.
4. Stocking may be irregular.
5. A manageable stand of advanced reproduction may be present.
6. In **mixed stands,** the overstory may be either (1) pure pine, or (2) a mixture of pine, spruce, and fir at the higher elevations, or pine and Douglas-fir at lower elevations. Understory trees have the same characteristics as pure stands except that the composition is likely to be other than pine.
7. Stocking in **mixed stands** is more likely to be irregular.
8. **Mixed stands** frequently have a manageable stand of advanced reproduction of species other than pine.

Recommended Cutting Treatments.—These are usually the most windfirm stands, even where they have developed from the deterioration of single- and two-storied stands. By the time they have reached their present condition, the remaining overstory trees are likely to be windfirm.

1. **Low to moderate windfall risk situations—**

There is considerable flexibility in harvesting these stands. All size classes can be cut, with emphasis on either the largest or smallest trees in the stand. The first cut can range from an **overwood removal** to release the younger growing stock to a **thinning from below** to improve the spacing of the most vigorous of the larger trees. Thereafter, cutting can be directed toward either even-aged or uneven-aged management. In **mixed**

Figure 33.—A multi-storied lodgepole pine stand.

stands the first cut should be an overwood removal of the pine to release the climax species. The understory trees should be thinned to improve spacing.

2. **High windfall risk situations**—

   The safest first cut is an overwood removal with a light thinning from below to obtain a wider spaced, more open stand that can develop windfirmness. Thereafter, cutting can be directed toward either uneven- or even-aged management.

Modification to Partial Cutting Practices Imposed by Disease and Insect Problems

Dwarf mistletoe.—

1. Cut only in stands where the average mistletoe rating is two or less (see fig. 24), and remove only the percentage of basal area recommended for the stand description and windfall situation. In **single-storied** stands, where site index is 70 or above, trees in the intermediate and lower crown classes should be removed first in preference to dominants and codominants. If site index is below 70, trees in all crown classes are about equally susceptible to infection. In **two-** and **three-storied** stands, as much of the first cut as is possible should come from the second and third stories because these trees are likely to be more heavily infected than the top story. In **single-, two-,** and **three-storied** stands, the final overstory removal can be delayed until the new reproduction is tall enough to provide a forest aspect. To minimize infection of new reproduction however, time interval should not exceed 30 years after the **regeneration cut** when the average mistletoe rating is one, or 20 years when the rating is two. Provision should be made to sanitize the young stand at the time of final harvest. In **multi-storied** stands, the safest procedure is an overwood removal with a cleaning and thinning from below.
2. In old-growth stands with an average mistletoe rating greater than two, any partial cutting, thinning, or cleaning is likely to intensify the infection. The **safest** procedure, therefore, is to either remove all of the trees and start a new stand or leave the stand uncut. If the manager chooses to make a partial cut for any reason, the initial harvest should be heavy enough to be a regeneration cut. **All** residual trees must be removed within 10 years after the first cut, and provision made to sanitize the young stand at that time.

Comandra Blister Rust.—Cut as many trees with stem cankers and spike-tops as possible in the first cut without removing more than the recommended basal area or cutting large openings in the canopy. Since the rate of spread in mature trees is relatively slow and the disease is not transmitted from pine to pine, leaving a few infected trees is less of a risk than opening up the stand too much.

Mountain Pine Beetle.—

1. If the insect is present in the stand at an endemic level, or in adjacent stands in sufficient numbers to make successful attacks, and:
   a. Less than the recommended percentage of basal area to be removed in the first cut is in susceptible trees, any attacked tree and all of the most susceptible trees should be removed in the first cut. This will include most of the trees 12 inches d.b.h. and larger, and all trees 10 to 12 inches d.b.h. in vigor classes A and B. Provision should be made to salvage attacked trees, and the second cut should be made within 10 years of the first cut.
   b. More than the recommended percentage of basal area to be removed in the first cut is in susceptible trees, the manager has three options: (1) remove all the trees, (2) remove the recommended basal area in attacked and susceptible trees and accept the risk of future losses, or (3) leave the stand uncut. If the stand is partially cut or left uncut, some trees from 7 to 12 inches d.b.h. and most trees below 7 inches d.b.h. will survive.
2. If the stand is sustaining an infestation that is building up, and the manager chooses to either partially cut or leave the stand uncut, he must accept the risk of an outbreak that could destroy most of the merchantable stand.

Cutting to Save the Residual

In **mixed stands** and to a lesser extent pure stands, the manager must determine whether he has an acceptable stand of advanced reproduction and decide if he is going to manage it before any cutting begins. Furthermore, he must reevaluate the advanced reproduction after the final harvest and slash disposal to determine the need for supplemental stocking. The same criteria used to evaluate advanced reproduction on spruce-fir clearcuts applies here.

In partial cutting, protection of the residual from logging damage is of primary concern. The residual includes merchantable trees left after shelterwood cutting, and advanced reproduction in both shelterwood and group-selection cutting where an acceptable stand is to be managed. Protection begins with a well-designed logging plan at the time of the first cut. To minimize damage, skidroads must be laid out — about 200 ft apart depending on the topography — and marked on the ground. These skidroads should be kept narrow, and located so that they can be used to move logs out of the woods at each cut. Close supervision of logging will be required to restrict travel of skidding and other logging equipment to the skidroads. In shelterwood cuttings, trees should be felled into openings as much as possible using a herringbone pattern that will permit logs to be pulled onto the skidroads with a minimum of disturbance. It may be necessary to deviate from the herringbone felling angle in order to drop trees into openings. If this is the case, the logs should be bucked into short lengths to reduce skidding damage. Trees damaged in felling and skidding should not be removed if they are still windfirm. In group-selection cutting, the felling pattern should be similar where there is a manageable stand of advanced reproduction. Otherwise all trees should be felled into the openings. Both shelterwood and group-selection cuttings require close coordination between felling and skidding because it may be necessary to fell and skid one tree before another tree is felled.

Slash Disposal and Seedbed Preparation

Some treatment of logging slash and unmerchantable material will probably be needed after each cut. Treatment should be confined to concentrations and that needed to reduce visual impact, however, because most equipment now available for slash disposal is not readily adaptable to working in shelterwood cuttings. Furthermore, burning slash will not only cause damage to the residual, but may destroy the seed supply in stands with serotinous cones. Skid out as much of the down sound dead and green cull material as possible for disposal at the landings or at the mill. Treatment in stands should be limited to lopping and scattering, chipping along the roadway, and hand piling and burning to minimize damage. In group-selection cutting, if there is not a manageable stand of advanced reproduction, dozers equipped with bush blades can be used to concentrate slash for burning in the openings. Piles should be kept small to reduce the amount of heat generated. Stands with the serotinous cone habit should not be treated until the cones have had time to dry out and open up.

On areas to be regenerated by new reproduction, a partial overstory canopy or trees standing around the margins of small openings provide two of the basic elements necessary for regeneration success in stands with the nonserotinous or intermediate cone habit — a seed source within effective seeding distance, and an environment compatible with germination, initial survival, and seedling establishment. In stands with the serotinous cone habit, the seed supply is largely in the cones attached to the slash or scattered on the ground. The manager must make sure that the third element — a suitable seedbed — is provided after the regeneration cut where shelterwood cutting is used, and after each cut where group selection is used. Unless at least 40 percent of the available ground surface is exposed mineral soil after logging and slash disposal, additional seedbed preparation is needed. Until special equipment is developed, seedbed preparation as well as slash disposal will pose problems. The equipment available is too large to work well around standing trees. Small dozers or other machines equipped with brush blades will have to be used, but they must be closely supervised to minimize damage to the residual.

Multiple-Use Silviculture

Timber production is only one of the key uses of lodgepole pine forests in the central Rocky Mountains. They occupy areas that also are important for water yield, wildlife habitat, recreation, and scenic beauty. Forest managers must consider how these areas are to be handled to meet the increasing demands of the public. The kinds of stands that appear desirable for increased water yields, preservation of the forest landscape, maintenance of scenic values, and improvement of wildlife habitat have been suggested in a general way by both research and observation.

WATER

Snowfall is the key to water yield in lodgepole pine forests. Comparisons on the Fraser Experimental Forest in Colorado have shown that more snow accumulates in cutover areas than under adjacent uncut stands. Accumulations are greatest on plots that are clearcut (Wilm and Dunford 1948, Hoover and Leaf 1967). The increased snow depth is not additional snow, however, but a redistribution of snow. Wind transports the snow intercepted on the surrounding

trees and deposits it in the openings. Some of the increase in water equivalent in the openings is available for streamflow (Hoover and Leaf 1967).

Research and experience suggest that a round or patch-shaped opening, about five to eight times trees height in diameter, is the most effective for trapping snow (Hoover 1969). In larger openings, wind is likely to dip down to the ground and blow the snow out of the openings. About one-third of the forest area in openings distributed over the watershed appears to be the best arrangement. These openings could either be maintained permanently or regenerated to new growth that would be periodically recut when trees reach about half the height of the surrounding trees. The remaining two-thirds of the area should be retained as continuous high forest, since the taller trees control snow deposition. Trees would be periodically harvested on an individual-tree basis or in small groups (one to two times tree height) to gradually replace the old with a new stand. Ultimately, the reserve stand would approach a broad-aged structure with the overstory canopy remaining at about the original height.

An alternative would be to make a light cut distributed over the entire watershed, removing about 20 to 30 percent of the basal area on an individual-tree basis or in small groups. The objective is to open up the stand enough to develop windfirmness, and salvage low-vigor and poor-risk trees. Openings five to eight times tree height can then be cut on about one-third of the area. The remaining two-thirds of the area would be retained as permanent high forest, with trees periodically removed on an individual-tree basis or in small groups.

Another alternative that would integrate water and timber production would be to harvest all of the old growth on a watershed with a series of cuts spread over a period of 120 to 160 years. At intervals of about 20 to 40 years, a portion of the area would be harvested in small openings — four to five times tree height — distributed over the watershed. The number of openings cut at each interval would depend on the size of the watershed and the length of rotation and cutting cycle selected. These openings would be regenerated (fig. 34) so that at the end of one rotation, the watershed would contain groups of trees in several age classes from reproduction to those ready for harvest. The tallest trees may be somewhat shorter than the original overstory, but the adverse effects on snow deposition should be minimized by keeping the openings small. At the end of one rotation, the forest manager has the option of following the same procedure through the next rotation, or selecting about one-third of the openings to be maintained as snow-trapping areas, and converting the remaining area into a broad-aged stand by periodically removing individual trees.

Figure 34.—New reproduction established in a cleared opening about four to five times tree height in lodgepole pine. Next series of group openings should be cut. Fraser Experimental Forest, Colorado.

WILDLIFE

The use of lodgepole pine forests by deer is influenced by timber cutting practices. On the Fraser Experimental Forest, there was more deer use and a greater abundance and selection of forage species on clearcut openings than under adjacent uncut stands (Wallmo 1969, Wallmo et al. 1972); openings 3 chains wide were used more than either wider or narrower openings. Forage production appears to decline about 10 years after cutting, however, as tree reproduction replaces forage species (Wallmo et al. 1972). Similar trends in forage production have also been observed on lodgepole pine clearcuts in Montana (Basile and Jensen 1971). Wallmo suggests that new openings be cut periodically.

An alternative would be to cut about one-sixth of a cutting block every 20 years in openings about four to five times tree height. Each Working Circle would be subdivided into a number of cutting blocks (of at least 300 acres) so that not all periodic cuts would be made in a single year on a Working Circle. Such periodic cutting would provide a good combination of numbers and species of palatable forage plants and the edge effect desired, while creating a several-aged forest of even-aged groups, thus integrating wildlife habitat improvement with timber production.

Observations on the Medicine Bow National Forest in Wyoming indicate that both natural and cleared openings in lodgepole pine forests are heavily used by elk for grazing and calving.[20] The size of opening does not appear to be critical, but openings interspersed with standing timber that can be used for ruminating, resting, and hiding are preferred. Since openings cut in the canopy are not likely to retain a high proportion of palatable forage species for long periods of time, new openings should be cut while allowing the older ones to regenerate.

Other wildlife, including nongame animals, living in lodgepole pine forests are affected by the way these forests are handled. In general, their habitat requirements include a combination of openings and high forest to provide food, cover, and edge. With protection from wildfires many stands have become denser, and reproduction has filled in the openings. Some reduction in stand density is needed to create or improve wildlife habitat. Small, irregular openings (about four to five times tree height) cut in the canopy at periodic intervals would open up the stand and provide the food, cover, and edge needed.

[20] *Personal communication with A. Lorin Ward, Wildlife Biologist, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

RECREATION AND ESTHETICS

Permanent forest cover — at least in part — is preferred in travel influence zones, and in areas of high recreational value and outstanding scenic beauty. Unfortunately, old-growth lodgepole pine stands are not likely to persist in a sound condition indefinitely. Where stand conditions and wind, insect, and disease problems permit, some form of partial cutting will retain forest cover while at the same time replacing the old with a new stand. However, the visual impact of logging operations — haul roads, damage to residual trees, and slash and debris — must be minimized. In situations where there is no alternative to clearcutting, and the environmental impact of clearcutting is unacceptable, there is no choice but to leave the stands uncut.

To reduce the sudden and severe visual impact on the landscape viewer, openings cut in stands for timber and water production, wildlife habitat improvement, and recreation (ski runs) should be a repetition of natural shapes, visually tied together to create a balanced, unified pattern that will complement the natural landscape (Barnes 1971). Such a pattern is especially important for openings in the middle and background that can be seen from distant views. The foreground should be maintained in high forest under some partial cutting system (again, where stand conditions and wind, insect, and disease problems permit).

MANAGEMENT OF YOUNG GROWTH

Throughout the Rocky Mountains there are extensive areas of second growth. These stands, which resulted from past fires or cutting, are between 1 and 120 years old. Many are badly crowded and in need of thinning to bring them under management. Some have been thinned at least once, but all need further reduction in stand density to maintain or reclaim lost growth.

Stand Description

Young stands may be pure or mixed. Pure stands are usually single-storied and even- or two-aged. Two-aged stands are occasionally two-storied with pine in the overstory and spruce, subalpine fir, or Douglas-fir in the un-

derstory. Pure stands are most often overstocked, while mixed stands may be patchy. In the thinning practices described below, no distinction is made between species. Trees with the best form and vigor, and free of disease should be left.

Thinning Practices

In stands with less than 2,500 stems per acre, the first thinning can be delayed until age 30 years. If the stand is 10 years old and the stocking is less than 1,000 stems per acre, the manager should consider fill-in planting to raise stocking to 1,500 stems per acre. The level of growing stock to be retained at age 30 will depend upon management objectives. Use the procedures developed by Myers (1971) to examine the possible alternatives. Select the growing stock level and cutting cycle that best meet the management goals for the particular combination of age, diameter, height, site quality, stand density, and past growth.

If the stand contains more than 2,500 stems per acre, it should be thinned at age 10 to 20 years. The first thinning should leave about 1,500 stems per acre. This density is needed to promote height growth in young stands. The second thinning should be made at age 30 years. The spacing will depend upon management objectives. Use the procedures developed by Myers (1971) to examine possible alternatives. From past growth in relation to diameter, height, age, density, and site quality, determine future growth for different combinations of growing stock and cutting cycles. Select the appropriate combination that best meets management goals.

If stands are 40 to 70 years old, wider spacings are recommended because height growth has been established, and that lost by crowding cannot be recovered. Some of the diameter growth can be recovered, however. Develop the necessary working tools from stand examination, and use the simulation program developed by Myers (1971) to produce a series of yield tables for different combinations of growing stock levels and cutting cycles. Select the combination that best meets management goals for the particular site and stand conditions.

Thinning in stands older than 70 years is not recommended unless original stand density was less than 2,500 stems. Even then the value of thinning is questionable because the cost is not likely to be recovered in terms of increased volume production.

WHAT DO WE NEED TO KNOW

Silvicultural practices are needed that will establish and maintain subalpine forest stands with the form, structure, and arrangement needed to integrate all land uses. For the timber resource, these needs include: (1) the ability to classify subalpine forests into categories of similar characteristics as the basis for identifying management potentials in existing stands; and (2) tests of new and modified silvicultural systems and cultural practices in stands of different characteristics.

The classification of vegetation in subalpine forests is needed to guide the manipulation of stands for multiple use. For the timber resource, this classification should include: (1) what species grow together, and how to recognize the plant associations; (2) how these species reproduce, grow, and interact in a variety of situations; (3) successional trends and stability of various plant associations in response to different management prescriptions; and (4) the extent to which research results can be extrapolated.

Prediction of growth and yield of even-aged spruce-fir is needed to provide the basis for decisions on (1) site quality classes that will repay the cost of thinning and other cultural treatments; (2) levels of growing stock — including frequency of thinnings and intermediate cuttings — to meet different management objectives; (3) length of rotation cutting cycles, and allowable cut for different cutting methods, management goals, and utilization standards, and (4) the place of timber management in multiple-use management. Managers can make better decisions about key uses when they can forecast timber potential under alternative management systems. The field and computer simulation techniques now available for the management of even-aged stands must be expanded to include uneven-aged stands and irregular stand structures needed for multiple use.

Methods of obtaining natural and artificial reproduction of Engelmann spruce have been largely directed toward regenerating cleared openings. While adequate regeneration practice can be prescribed in most instances, information is still needed on: (1) relationships between the kind of seed source and the amount and periodicity of seed production; and (2) germination and survival under different environmental conditions to identify limiting factors and provide estimates of the probability of seedling establishment. These data, together with existing information on seed dispersal distances will permit simulation of the regeneration phase of spruce for different environmental conditions.

Methods of obtaining regeneration are usually adequate for lodgepole pine stands with serotinous cones. What is needed now are natural and artificial reproduction procedures for stands with nonserotinous cones, especially on south slopes and in tension zones.

There is a need to use quantitative data from existing knowledge in current resource and prediction response simulation models to aid multiple-use planning and decisionmaking. These models will also identify deficiencies in knowledge where additional work is needed to determine basic processes and interrelationships among various resources and management practices. We must pinpoint and fill in these gaps in our knowledge before we can develop more refined multi-resource response models.

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SILVICULTURE OF SOUTHWESTERN MIXED CONIFERS AND ASPEN:

The Status of Our Knowledge

By John R. Jones

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Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado

USDA Forest Service
Research Paper RM-122
May 1974

ABSTRACT

Describes the status of our knowledge about mixed conifer silviculture in the interior Southwest. Ecological background is reviewed first, followed by description of silvicultural methods. Relevant literature is discussed, along with observations, experience, and results of unpublished research. Contains unpublished input by subject-matter specialists and southwestern forest managers, largely as feedback from their reviews of a working draft. Research needs are also considered. Aspen forests are included; in the Southwest they are usually succeeded by mixed conifers.

Oxford: 614. **Keywords:** Silviculture, forest regeneration, *Abies concolor, A. lasiocarpa* var. *arizonica; Picea engelmannii, P. pungens; Pinus ponderosa, P. strobiformis; Populus tremuloides; Pseudotsuga menziesii* var. *glauca.*

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USDA Forest Service
Research Paper RM-122

May 1974

SILVICULTURE OF SOUTHWESTERN MIXED CONIFERS AND ASPEN:

The Status of Our Knowledge

by
John R. Jones, Principal Plant Ecologist
Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University; author is located at the Station's Research Work Unit at Flagstaff, in cooperation with Northern Arizona University.*

PREFACE

In any field there is a periodic need to describe the status of available knowledge — to gather unpublished information and that which is scattered in various reports, and organize it in one set of covers for easy reference. That has been done here. Recommendations will often be somewhat tentative and less than precise. While there is much we still need to find out about the silvics and silviculture of mixed conifer land in the Southwest, there is much we already know.

Although reference is made here and there throughout the paper to management for other purposes, it is directed toward the growing of timber. Other writers are summarizing the water, wildlife, and range aspects of forest management. Much of the silvical discussion here, however, and many of the silvicultural methods described, are directly applicable or readily adaptable to management for purposes other than growing timber.

Early sections of the paper describe the Southwestern mixed conifer forests and their silvics. Later sections discuss their silviculture. A final brief section looks at needed research.

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SILVICULTURE OF SOUTHWESTERN MIXED CONIFERS AND ASPEN:
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John R. Jones

GENERAL DESCRIPTION OF THE MIXED CONIFERS

Mixed conifer forests occupy sites more moist than those usually occupied by pure stands of ponderosa pine.[2] Pinyon-juniper woodlands and the variable mixtures of Chihuahua pine, Apache pine, and evergreen shrubs are not mixed conifer forests within this definition. The common overstory species in mixed conifer forests are Douglas-fir, ponderosa pine, white fir, Engelmann spruce, aspen, southwestern white pine, blue spruce, and corkbark fir, often in more or less that order of abundance. In some mixed conifer areas of the Southwest, one or more of those species may be absent. Corkbark fir is replaced by the closely related subalpine fir on the Kaibab Plateau. In this paper, Southwest means Arizona, New Mexico, and the San Juan Basin of southwestern Colorado.

Mixed conifer forests may be any one of a diversity of mixtures. Various combinations of the above species can be found, with as few as two or as many as all eight growing intermixed. Mixed conifer stands have this in common: the moisture regime has permitted the more or less abundant establishment of coniferous species whose seedlings are more sensitive to drought than are ponderosa pine seedlings. At one extreme the overstory may be almost pure ponderosa pine, with other species abundant only in the understory. At the other ecological extreme, the stand may be predominantly Engelmann spruce and corkbark fir.

Ordinarily, stands of mixed Engelmann spruce and corkbark fir without other species are not considered mixed conifer forest. They form a distinctive and easily defined cover type logically regarded as an extension and variant of the Engelmann spruce-subalpine fir forests farther north, whose management is described in detail in another publication (Alexander 1974). In the Southwest, however, Engelmann spruce-corkbark fir stands intergrade with mixed conifer stands. They are ecologically similar to them in important respects, are often associated with them, and both component species are also elements in mixed conifer forests. In this paper, therefore, Engelmann spruce-corkbark fir forests will occasionally be considered. For convenience, they will be referred to simply as spruce-fir forest. Some foresters and related specialists in the Southwest extend the term spruce-fir forest to include mixed conifer forests that contain spruce. In this paper the term will be used in the more usual sense and not be applied to stands with appreciable mixtures of other species except for groups of aspen.

Aspen forests in the Southwest typically tend to be replaced in time by mixed conifer or spruce-fir forest, and often have a mixed conifer or spruce-fir understory. Aspen management is therefore closely tied to mixed conifer and spruce-fir management, and for that reason will also be discussed here.

A discussion of succession and climax in mixed conifer forests can best follow a discussion of ecological factors. For now let it suffice to say that, following destruction of mixed conifer forest by fire, epidemic, or clearcutting, succession commonly begins with aspen, meadow, or shrub communities. Eventually the area returns to mixed conifer forest, and some mixed conifer forests evolve into spruce-fir forest.

DISTRIBUTION

The principal mixed conifer forest areas (fig. 1) include about 2½ million acres of mixed conifer forest broken by associated grassland, aspen forest, ponderosa pine forest, and brushland. As mapped, they include the spruce-fir areas of New Mexico and Arizona but not of southwestern Colorado.

In addition to the areas mapped — areas where mixed conifer forest predominates — mixed conifer stands are scattered in areas predominantly of ponderosa pine forest, where higher elevations, protected north-facing slopes, and the bottoms of canyons and draws provide suitable moisture regimes.

Mixed conifer stands can be found below 6,000 ft in canyon bottoms and on steep north slopes, but most occur at elevations above 8,000 ft. Pure ponderosa pine stands can also be found well above 8,000 ft, probably most often because seed sources of other species are inadequate for effective invasion.

[2]*Scientific names of plants and animals mentioned are listed on page 44.*

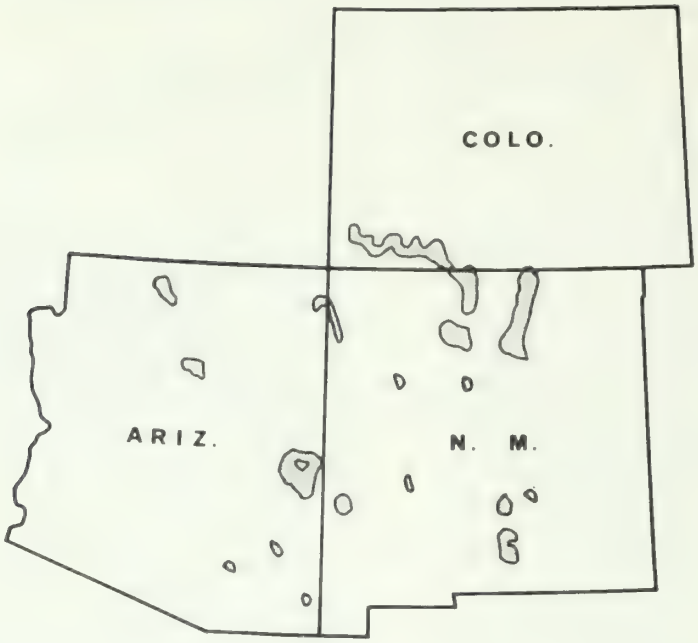

Figure 1.—Main mixed conifer areas in the Southwest.

Mixed conifer stands are largely replaced by spruce-fir at elevations a little below 10,000 ft. Coniferous species other than Engelmann spruce and corkbark fir persist above 10,000 ft mainly as scattered individuals on south slopes or exceptionally rocky ridge tops. Spruce-fir stands can also be found as low as 8,500 ft, primarily on northerly slopes and usually with some slight mixture of other conifers.

Spruce-fir forest may extend to 12,000 ft on favorable sites. Corkbark fir seldom if ever persists to timberline.

ECOLOGICAL FACTORS INFLUENCING SILVICULTURE

Ecological processes tend to be complex interactions of various organisms and assorted physical factors. A single factor may or may not dominate. It is convenient and useful, however, to consider factors individually, with the understanding that they operate jointly.

Moisture

At winter's end, mixed conifer soils are wet. During the following spring-early summer dry season, varying degrees of soil moisture stress develop (Embry 1971). These moisture stresses apparently are not severe enough to critically affect established seedlings or larger trees except where competition is severe (Jones 1972). On southerly slopes or level sites, a heavy stand of grass will lower soil moisture to critical or fatal levels for tree seedlings. These levels may extend from the soil surface to a depth of at least 16 inches (Embry 1971) and presumably more. On northerly slopes, drying under grass is less severe. In contrast, drying of bare loam soils commonly is severe only in the upper inch or two; there is usually considerable moisture 3 or 4 inches beneath a bare surface, even on southerly slopes (Embry 1971).

Studies with various conifers outside the Southwest indicate that soil moisture stress slows seedling height growth substantially when the soil still contains considerable available moisture (Brix 1962, Glerum and Pierpoint 1968, Jarvis and Jarvis 1963, Stransky and Wilson 1964). Mixed conifers achieve most of their height growth in the Southwest before the summer rains begin, using winter moisture stored in the soil.

Summer rains, which usually begin the first half of July, rewet the soil. Moisture stresses, even under a grass cover, are unlikely to become severe again on mixed conifer sites until autumn. Autumn is often dry, but herbaceous cover has largely cured by then so soil drying is less severe than in spring. Also, trees have stopped growing except for root tips, and seem to be relatively drought resistant in autumn.

Some seedbeds, especially duff, dry out quickly. In years and locations where rains are sporadic in July, this drying may delay germination and kill newly emerged seedlings. On the other hand, a thin layer of needle litter on

nineral soil may act as a mulch, and may also educe the foraging efficiency of seed-eating odents. If seeds are naturally or artificially overed by a thin layer of mineral soil they are ess subject to drying, and therefore germinate uicker and survive better.

Temperature

During the period of active stem elongation, rimarily the month of June, nighttime mperatures are still quite cool — commonly in ie 30° F range. Soil warming is retarded. hysiological studies with various species in- cate that seedling growth under these con- tions is considerably restricted. Where cold air ollects at night, severe frosts in June may also ll back new growth (Ronco 1967).

Sequences of freezing and thawing when the oil is wet and bare of snow often result in xtensive frost heaving of seedlings. Freezing ithout alternating thawing causes much less vere heaving. Deeply rooted seedlings frost eave less than those with shallow roots. In a rge spot-seeding study in clearcuttings with ee air drainage, blue spruce was seeded as a n-tolerant species with shallow seedling ots, and white pine was seeded as a sun- lerant species with deep seedling roots. Many the blue spruce seedlings that survived the rst growing season were subsequently frost eaved, while relatively few white pine edlings were frost heaved. Had air drainage en poor at night, frost heaving presumably ould have been even more severe.

Juvenile roots of Engelmann spruce are about s shallow as those of blue spruce, and seedlings e easily frost heaved. Corkbark fir and ouglas-fir seedlings root a bit more deeply eir first year. White fir, white pine, and nderosa pine seedlings, which root much ore deeply, are relatively resistant.

When Douglas-fir tubelings were planted on a earcutting, they all frost heaved, with their 3- ch tubes, although frost heaving on adjacent hite pine seedspots was not serious.

Frost heaving requires a soil texture suited to e upward movement of water in response to eak moisture gradients. Sands do not frost eave. Soils with a high silt content are especial- l susceptible.[3] Many Southwestern forest soils e silt loams or silty clay loams.

Prolonged snow cover on north-facing slopes otects seedlings from alternate freezing and awing, and therefore reduces frost heaving. In contrast, on some south-facing slopes the snow may melt even in midwinter, saturating the surface soil and exposing it to alternate freezing and thawing.

Shade not only prolongs snow cover; it considerably reduces both the daytime thawing of bare ground and the incidence of ground freezing in early autumn and late spring when there is no snow cover (Graber 1971).

Light

Open sunlight is always sufficient for good growth (Hodges 1962). There may, however, be too much light. In the Southwest, Engelmann spruce, corkbark fir, Douglas-fir, and white fir do not readily invade openings except in shade, commonly of fallen timber, aspen regrowth, or a forest edge (fig. 2). These observations coincide with research results in southern New Mexico (Krauch 1956) and elsewhere in the interior West (LeBarron and Jemison 1953, Ryker and Potter 1970).

Work in Colorado showed that unshaded Engelmann spruce seedlings, planted in the open at age 4, suffered very heavy **overwinter** mortality. Matched seedlings shaded during the summer with upright shingles suffered few overwinter deaths. A process called solarization, taking place within exposed seedlings during the summer, caused them to die under the snow (Ronco 1967, 1970a, 1970c). A comparable process may occur in Douglas-fir (Zavitkovski and Woodard 1970) and other species.

One-yr-old seedlings were planted in Arizona to learn whether solarization operates in mixed conifer forests here. Ponderosa pine and aspen were not included. Unfortunately, the study was compromised by two consecutive winters with record low snowfall and relatively short periods of snow cover; the hypothesized process hardly had a chance to become critical. Nonetheless, shaded seedlings of all species survived considerably better than unshaded seedlings. All unshaded corkbark fir seedlings and almost all unshaded Douglas-fir died, although few died over winter. Whether solarization was involved or not, shade was clearly very beneficial.

Healthy seedlings grown for 2 or 3 yr in a nursery and properly planted in the field are much more resistant to the drying and heating effects of exposure to full sunlight than are recently germinated seedlings. If a species is subject to solarization, however, seedlings several years old can still be quite susceptible. In Colorado and New Mexico, a number of plantations of 2- and 3-yr-old Engelmann spruce

[3] *Personal communication from L. J. Heidmann, Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, Flagstaff.*

Figure 2 —Dense Engelmann spruce regeneration that came up in the shade of jack-strawed blowdowns after a fire. Apach National Forest.

have failed, apparently because of solarization. A few unshaded Engelmann spruce plantations, including one in Arizona, have survived and grown well. The reasons for these exceptions are not known.

In some regions and types, heat girdling causes heavy losses of newly germinated seedlings on bare southerly slopes. Radiant heating of the ground surface kills juvenile tissues in the hypocotyl. Seedlings more than 8 to 12 weeks old usually are no longer susceptible (Baker 1929, Keijzer and Hermann 1966). Seedspot studies suggest that heat girdling is not a major source of seedling deaths in southwestern mixed conifers that germinate after the summer rains begin. The rainy season is cloudy and the soil, usually wet at or near the surface, probably seldom heats severely. Heat girdling may be significant among new seedlings of corkbark and white fir because they germinate in the sunnier spring.

Because of poor heat conductivity and low moisture content, sandy soils are more likely than loams or clays to reach critically high temperatures (Chang 1958).

Wind

Wind blows down trees, distributes seed contributes to drying, and influences plant and ground temperatures.

WINDFALL

Windfall is a function of windspeed, tree form, firmness of rooting, and strength of stem.

Alexander (1964, 1967b) studied factors influencing blowdown along the margins of clearcuttings in Colorado. Many of the same factors are pertinent to blowdown in partially cut or uncut timber (Alexander 1973).

Destructive winds are most likely after the spring thaw and during occasional fall storms, when they come mainly from the southwest. Destructive winter winds may blow from the northeast. In any locale, observation of fallen trees suggests the directions from which destructive winds are likely.

Topographic situations where windfall risk is below average, above average, or very high have been summarized by Alexander (1974) as follows:

Below average —

1. Valley bottoms, except where parallel to the direction of prevailing winds, and flat areas.
2. All lower, and gentle middle north- and east-facing slopes.
3. All lower, and gentle middle south- and west-facing slopes that are protected from the wind by considerably higher ground not far to windward.

Above average —

1. Valley bottoms parallel to the direction of prevailing winds.
2. Gentle middle south and west slopes not protected to the windward.
3. Moderate to steep middle, and all upper north- and east-facing slopes.
4. Moderate to steep middle south- and west-facing slopes protected by considerably higher ground not far to windward.

Very high —

1. Ridgetops.
2. Saddles in ridges.
3. Moderate to steep middle south- and west-facing slopes not protected to the windward.
4. All upper south- and west-facing slopes.

Trees on shallow or poorly drained soils root shallowly and are windthrown more easily. Trees with root rot are also windthrown more easily, while those with trunk rot break more easily. Trees with long crowns generally are less likely to blow down, and recently exposed trees previously grown in dense even-aged stands tend to be substantially more susceptible than overstory trees grown in open or uneven-aged stands.

Even long-crowned lowerstory trees are very susceptible to windfall if exposed too abruptly. One-step overstory removal may result in heavy blowdown of newly exposed poletimber, including trees with live crowns reaching the ground. Such blowdown can happen even from storms causing little blowdown among the occasional short-crowned overstory culls that are left.

Understory saplings seem much less subject to postlogging blowdown than understory trees 4 inches in diameter or larger.

It seems likely that, other things being equal, species with broad, deep root systems and strong wood are more resistant to blowdown than other species growing on the same site. Other factors tend to obscure the species relationship, however, except that newly exposed aspens are exceptionally susceptible to windthrow.

Blowdown is sometimes heavy along the margins of clearcuttings. While the forester who lays out the boundaries of patches to be clearcut is considering such factors as overstory condition, dwarf mistletoe, esthetics, and advance regeneration, he should also look at topographic and stand characteristics, and locate boundaries to minimize blowdown as much as other considerations permit. Alexander's guidelines for spruce-fir forests (Alexander 1974) seem largely appropriate to mixed conifer forests, and are adapted below in part:

1. Protection from wind for the vulnerable downwind boundary is most important.
2. Do not locate cutting boundaries where they will be exposed to winds funneling through exposed saddles to the south or west.
3. Avoid locating cutting boundaries on ridgetops or near saddles, especially ridgetops of secondary drainages downwind from and at right angles to the main drainage when the main drainage is a narrowing valley with steep sides. Any such ridgetop should either be cut or left uncut for at least 200 ft down on both sides.
4. So far as other considerations permit, lay out each unit so the maximum amount of cutting boundary is parallel to the contours.
5. Irregular cutting boundaries without sharp indentations or projections or square corners will reduce blowdown.
6. Do not locate boundaries on poorly drained or shallow soils.
7. Locate boundaries where stand conditions favor windfirmness: (a) stands of sound trees; (b) immature stands; and (c) poorly stocked stands.

SEED DISTRIBUTION

Studies in the southern Rocky Mountains and Southwest (Alexander 1969, Jones 1967b, Ronco 1970b) have demonstrated the importance of wind in the distribution of seed into openings. Much more seed falls on the upwind part of an opening than on the downwind part, and most falls within about 100 ft of the edge. If the upwind part is also upslope, the combined effect can be particularly heavy seedfall over a relatively short distance into the opening.

To receive abundant seed, a clearcut should not be wider than about 200 ft in the direction of the prevailing autumn wind. If conditions are excellent for seedling establishment, however, adequate regeneration may occur over somewhat greater distances. Where environments are unfavorable for regeneration, few seedlings will become established regardless of abundant seed.

OTHER EFFECTS

Winds increase evaporation and transpiration (Meyer et al. 1960) and consequently should increase seedling moisture stress (Jones 1972) and soil drying. Winds reduce the peaks of soil surface temperatures, however, reducing the danger of heat girdling. The frequency and severity of freezing near the ground is also reduced by night winds (Geiger 1957).

Ring shake in large Douglas-fir is often attributed to wind and is commonly called "wind shake", although it is not clear whether wind actually is the cause.

Biotic Factors

COMPETITION

Competition for moisture can seriously delay the regeneration of mixed conifer openings. Heavy grass stands dry the soil severely (Embry 1971), particularly grasses such as Arizona fescue and orchardgrass that make rather vigorous dry-season growth (Schubert et al. 1970). Specific information on soil moisture depletion by sedges and forbs that grow during the dry season is not available. Some may compete as severely as spring grasses.

Bunchgrasses such as Arizona fescue may not appear to fully occupy a site because their aboveground parts form clumps surrounded by bare ground. Commonly, however, their roots fully occupy the soil between the clumps.

Trees and shrubs also deplete soil moisture, but moisture remains available under mixed conifer, spruce-fir, and aspen stands throughout the dry season (Patten 1963, Pearson 1931), even in the upper inch of soil (Pearson 1931).

In mixed conifer and spruce-fir forests, competition for light is important. Understory seedlings grow very slowly, at least partly because of limited light, and growth may be substantially improved when the overstory is thinned or removed (Jones 1971). Release even from the modest shade of aspen canopies substantially increases the growth of understory conifers (Lees 1966, Pearson 1914). The different shade tolerances of mixed conifer species will be discussed later under Some Species Characteristics.

Some plants introduce chemicals into the soil that reduce conifer germination and interfere with normal growth. It is not clear how important this may be under field conditions.

Recent Polish research has demonstrated that at least some grasses also withdraw nutrients from the soil much more aggressively than do competing coniferous seedlings (Fober and Giertych 1971). Competition for nutrients may prove to be a significant factor in seedling survival and development.

In an Arizona study, vigorous ponderosa pine and Engelmann spruce seedlings were planted in a stand of orchardgrass and watered weekly until well into the first rainy season. Others were planted on sites where the grass had been eliminated, and were not watered. After three growing seasons, survival under both conditions was similar — fair for ponderosa pine and excellent for Engelmann spruce — but all the seedlings planted in grass were in poor condition. They had grown very little, and all the spruce were a brassy greenish-yellow color. The most vigorous of the ponderosa pine seedlings added only 6.5 inches of height over three growing seasons. Only one Engelmann spruce grew more than 4.5 inches. On the sites initially without grass, many seedlings added more than 10 inches to their heights during the same period, and a few added more than 20 inches, despite development of variable competition with aspen, raspberries, forbs, bracken, and some grass.

Another effect usually included under competition is the burial of small seedlings by dead herbaceous material or aspen leaves (Canada Forestry Branch 1967, Hughes 1967, Koroleff 1954, Pearson 1914, Pratt 1966). Typical seedlings of Douglas-fir, true firs, and the spruces are less than an inch tall at the end of their first growing season (Jones 1971), and easily buried. Many seedlings, especially

Douglas-fir, covered by dead plant material during the winter, are killed by damping-off fungi (Tappeiner and Helms 1971).

BIRDS

In some regions, birds are major predators on tree seed and newly emerged seedlings (Noble and Shepperd 1973). Juncos have been seen taking seed from seedbeds in the Southwest, and other southwestern birds are known to eat tree seed, but limited experience in seeding suggests that birds are not often serious predators on mixed conifer seed.

White pine seed is large and wingless, yet white pine seedlings can be found well away from a seed source, often in tight clumps and in openings. While rodents may often have buried the seeds, the distances involved frequently suggest birds as the agents.

Birds are important factors in the dynamics of insect populations. Many birds feed on defoliating caterpillars. In some areas woodpeckers have destroyed virtually the entire brood of the spruce beetle (Massey and Wygant 1954).

SMALL MAMMALS

The scope and seriousness of rodent damage to regeneration efforts in southwestern mixed conifers has been abundantly demonstrated. A number of studies have established that seed in unprotected artificial and natural seedings often is almost all taken by rodents (Jones 1967b; Krauch 1936, 1942a, 1942b, 1942c, 1945). Losses are credited largely to deer mice, although ground squirrels, and also shrews (Kangur 1954) are known to eat significant amounts of seed. Newly germinated seedlings too are preyed upon by rodents, and losses on seedspots may approach 100 percent (Jones 1967b, Krauch 1936, Ronco 1967). A planting of Douglas-fir tubelings in Arizona was completely eliminated by rodents within a few nights. Meadow voles are apparently the chief predators on newly emerged seedlings and young tubelings.

Rodent problems are common in coniferous regions, and a considerable literature has developed. Coating seed with endrin has sometimes given effective protection, as has rodent reduction with poisoned baits. Reinfestation from the perimeter of baited areas is quick, however. Deer mice forage widely, with individuals traveling as far as 2 miles (Hooven 1958).

Rodents that eat seeds are much less numerous in the forest than in meadows, burns, or clearcuttings. And rodents do not have an unlimited capacity to find and consume. Where a very large amount of seed falls, even in the open, much of it commonly survives to germinate.

Established seedlings are not immune to rodent damage. Pocket gophers have severely damaged or even eliminated coniferous plantations in some regions (Crouch 1971, Hooven 1971, Ronco 1967). Plantation experience in the Southwest is relatively recent and limited, but here, too, they have damaged plantations both of ponderosa pine and Engelmann spruce. Pocket gopher damage is done mostly in winter and spring when the preferred succulent forbs are unavailable. It is rather easy to identify: the roots may be cut, leaving the drying seedling tilted and easy to pull up. Or the gopher may burrow beneath the seedling and pull it partly or entirely into the ground. Pocket gophers also forage aboveground, especially under the snow, and debark seedlings, leaving rather distinctive tooth marks about 1/16 inch wide. During some winters, well-established seedlings may be debarked and killed by meadow voles, but losses apparently are seldom serious.

At times porcupine damage may be locally severe on saplings, poles, and sawtimber, and occasionally on large seedlings. Rabbits and hares are not known to damage southwestern mixed conifer forests significantly.

Small mammals also have desirable effects. For example, shrews and deer mice eat large numbers of insects, and pocket gophers much prefer competing succulent forbs to tree seedlings. Rodent burrowing can be important in keeping soil highly permeable to water and limiting runoff rates in coniferous forests, where water-repellent layers sometimes develop beneath the litter layer (Meeuwig 1971). But the benefits become academic when rodents reach numbers incompatible with timely reforestation. Fortunately, drastic reduction of rodents by poisoning is very temporary. Strategic timing can give the desired benefits with minimum short-lived side effects.

LIVESTOCK

Where sheep are numerous in mixed conifer areas, they browse all species of regeneration severely (except bristlecone pine). Baker (1925) stated that successful aspen regeneration is not possible where sheep are pastured. Where aspen suckering is abundant and vigorous, however, controlled moderate use of the area by sheep allows satisfactory aspen development, par-

ticularly if sheep are excluded the first year (Smith et al. 1972).

Cattle usually graze mixed conifer cutovers. It is often difficult to separate cattle damage from damage by big-game. In the Southwest, cattle sometimes browse ponderosa pine severely. Most damaged seedlings eventually grow out of reach of further browsing, however, and outgrow the distortions of form that developed. The major loss is likely to be the years of growth lost. Historically, grazing pressures were often much heavier than now, and many seedlings were killed.[4] Today, cattle browse seedlings mostly where herbaceous forage is seriously deficient during the period of shoot extension, mainly in June, or where cattle concentrate, as near salt blocks and water tanks. On well-managed ranges, browsing damage by cattle is usually trivial.

Trampling by cattle is more general, and the damage done is generally proportional to intensity of cattle use. In a recent planting study, a salt block was left next to a plot for a few days. Although damage from browsing was minor, trampling damage was considerable. Douglas-fir seedlings planted beneath an aspen stand were severely and repeatedly broken by cattle over a 15-yr period. Although survival was fair, all the trees were low and distorted. None had outgrown the damage.

Abundant slash on an area protects seedlings from both trampling and browsing.

BIG-GAME

Deer have seriously browsed regeneration in some areas. The importance of browsing by elk is less clear, because where elk are present, so are deer. The amount of damage differs by tree species. The approximate order of browsing preference from most to least seems to be: aspen $>$ ponderosa pine $\simeq$ white fir $\simeq$ corkbark fir $\geq$ Douglas-fir $>$ white pine $\simeq$ Engelmann spruce $\simeq$ blue spruce.

Severity of damage is related to the density of game populations near regeneration areas, and the availability of preferred forage species. Another factor is the extent of heavy cuttings or burns in an area: small acreages receive more concentrated game use. On very large areas, such as the Escudilla Mountain burn in eastern Arizona, aspen regenerated successfully even during a period of high game populations. On the 90 acres of clearcuttings at Burro Mountain, 20 miles away, the initially abundant aspen regeneration was completely eliminated by browsing (Jones 1967b).

A Utah study (Smith et al. 1972) and other observations suggest, however, that such elimination happens only with abnormal browsing pressures. Two ponderosa pine plantations at Burro Mountain were essentially eliminated by game browsing during a period of high deer and elk numbers (Jones 1967b). A few years later, deer and elk numbers were considerably lower. Newer clearcuttings on the same forest had developed large patches of aspen saplings, and browsing of study plantations was trivial, even though cattle were present in addition to big-game.

Big-game, especially elk, kill some small seedlings by trampling. In a recent seeding study, 187 of 600 seedspots were disturbed during 2 years by elk, cattle, or deer, in that order of frequency. Many seedlings were stepped on, but most straightened and recovered. Where spots were scuffed, however, seedlings commonly broke or were partly uprooted.

Elk feed on and scar aspen bark rather widely.[5] In some elk wintering areas in Wyoming and Colorado, the damage to aspen stands is heavy. Resulting physiological stress, insect attack, and fungal infection may cause serious mortality which, with associated browsing of suckers, is resulting in gradual conversion to grassland (Krebill 1972). This has so far not been a problem in the Southwest, where elk do not concentrate in aspen areas in winter.

INSECTS

Among the important pests of mixed conifer forests are bark beetles, which depend mainly on overmature or damaged trees to reach outbreak levels. Once outbreak levels have been reached, young vigorous trees may also be killed. Bark beetle outbreaks are most likely to develop during drought years. Outbreaks may develop in heavy blowdown, in trees damaged by forest fire, in concentrations of large logging slash, or in stands badly weakened by defoliating insects.

One of these bark beetles, the spruce beetle, is sometimes very destructive of spruce-fir forests

[4] *Krauch, H., and G. A. Pearson. 1930. Recovery of western yellow pine injured by grazing animals. (Unpublished report in the files of the Rocky Mountain Forest and Range Experiment Station, Flagstaff.) Eight thousand seedlings were studied. A photographic history was compiled of the development of 87 seedlings from 1914 to 1928.*

[5] *Hinds, T.E., and R. G. Krebill. Wounds and canker diseases of western aspen. U.S. Dept. Agric. For. Serv., For. Pest Leafl. (In press.)*

Figure 3.—Engelmann spruce forest wiped out by spruce beetles. The dead trees were cabled down in order to burn the unsalvageable debris. Carson National Forest.

(fig. 3). It is not known to be a threat to mixed conifer stands except where spruces predominate. Its biology and control were described by Massey and Wygant (1954) and more recently by Schmid and Beckwith (1972) and by Schmid (1972). Outbreaks can be stopped by removing infested trees, or by felling followed by spraying or burning infested trunks. Spraying insecticide on the lower trunks of standing infested trees contributes to control. Trap trees, intentionally felled prior to beetle flight, attract beetles and tend to concentrate them. After the beetles have entered the downed trees, the logs may be hauled away for sawing, treated chemically, or removed and burned. Recently, cacodylic acid has been injected in trap trees before felling. The trees are attacked but no brood develops, so the trees need not be disposed of later (Buffam 1971).

Sufficiently cold weather, particularly during early winter, may collapse a spruce beetle outbreak, especially if the snow is not yet deep. Woodpeckers eat large numbers of spruce beetles and their larvae, and may virtually destroy the brood in a locale. Several insect species parasitize or prey on the beetles, their larvae, or pupae.

The Douglas-fir beetle kills many overmature and mature Douglas-firs. Outbreaks, which usually develop following disturbances such as blowdown or defoliation, or in logging slash (Furniss and Orr 1970), sometimes nearly eliminate merchantable Douglas-fir from a stand. The most damaging outbreaks of Douglas-fir beetle in the Southwest have been associated with drought.[6]

Local outbreaks of the fir engraver occasionally damage white fir severely in some locales (Stevens 1971). Outbreaks seem likeliest during or just after drought years.

Several species of bark beetles that damage ponderosa pine forests seem unimportant in mixed conifer forests. These include the mountain pine beetle, the roundheaded pine beetle, and the Arizona five-spined engraver (*Ips*). They may, however, damage mixed conifer stands where ponderosa pine predominates. Lucht et al.[7] reported roundheaded pine beetles killing pines in a south-slope pole stand predominantly of ponderosa pine. Death of the pines was tending to release the Douglas-fir understory and speed succession.

Outbreaks of defoliators may develop in vigorous young forests as well as in overmature stands. The western budworm periodically damages Douglas-fir and white fir in some areas. The insect was recently reviewed by McKnight (1968). Outbreaks may result in extensive dieback but the trees commonly recover. Defoliated trees are also subject to serious attack by bark beetles (Whiteside and Carolin 1961). Growth is reduced in any case, and dead leaders commonly serve as centers of subsequent decay. Sapling stands have been rendered worthless by epidemics of this insect. Since the western budworm is dependent on new foliage for normal development and fecundity, a late freeze may not only kill larvae directly but may cause starvation by killing back the new shoots. During their winter hibernation, however, even the coldest weather does not seem to harm the larvae.

Occasional outbreaks of the Douglas-fir tussock moth result in locally severe mortality and topkill in all age classes. In the Southwest, the known outbreaks have developed with white fir as the primary host (Wickman et al. 1971), but outbreaks probably could develop with Douglas-fir or corkbark fir as primary hosts.[8] During an outbreak, all associated conifers are likely to be defoliated. The insect is attacked by birds, various insects, and a virus

[6] *Personal communication from Frank Yasinski, branch of pest detection and control, Southwestern Region, USDA Forest Service, Albuquerque.*

[7] *Lucht, D. D., R. H. Frye, and J. M. Schmid. Emergence and attack behavior of* Dendroctonus adjunctus *near Cloudcroft, New Mexico. (Manuscript in preparation at Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.)*

[8] *Personal communication from Robert Frye, branch of pest detection and control, Southwestern Region, USDA Forest Service, Albuquerque.*

disease, and outbreaks are usually shortlived (Wickman et al. 1971).

Another defoliator, the New Mexico fir looper, has occasionally damaged and killed considerable Douglas-fir, true firs, and spruce.

The western tent caterpillar[9] periodically defoliates aspen stands in northern New Mexico, southern Colorado, and Arizona's Kaibab Plateau. Stem analyses of old aspens indicate that, in other areas, it does not reach (or at least does not sustain) epidemic proportions. Severe outbreaks may last several years, and are always accompanied by severe reduction in aspen growth. Top dieback may be extensive. Some large stands may be essentially destroyed (fig. 4), with most trees dead and the survivors having severe topkill (Stelzer 1968). Limited observation suggests that such devastated stands generate suckers only weakly.

Figure 4.—Aspen stand in New Mexico 1 yr after collapse of tent caterpillar outbreak. Most trees are dead (Stelzer 1968).

Western tent caterpillar outbreaks usually persist for several years before being ended by predatory or parasitic insects, disease, or starvation. Meanwhile repeated defoliation may damage or destroy stands on many thousands of acres. Theoretically, introduction of an effective natural disease early in an outbreak could collapse the outbreak before serious damage is done. Research on spraying outbreaks with water suspensions of *Bacillus thuringiensis* Berliner and a nuclearpolyhedrosis virus (Stelzer 1967, 1971) have been encouraging.

The southwestern pine tip moth kills the growing tips of ponderosa pine seedlings and saplings, and has caused considerable damage to some pine-zone plantations. Seedlings may be attacked the same spring they are planted. Trees may become forked or crooked, especially when attacked for 2 or more years. It may be that, when plantations and young stands become more widespread in the mixed conifer zone, this insect will be a problem there too.

Insects not now known to be potential problems in Southwestern mixed conifer forests may yet prove troublesome. Recently the white fir needle miner has infested the white fir on about 10,000 acres of the Apache National Forest. Serious topkill or branchkill is not expected but the outbreak is being monitored.

DISEASES

The most important diseases of mixed conifer forests in the Southwest are trunk rots and dwarf mistletoes. Trunk rots and cankers are the major aspen diseases. As management becomes more intensive and research more advanced, diseases not yet appreciated may also prove quite important.

Fungal Diseases. — Trunk rots are widespread in overmature trees. Some species are more affected than others. In old virgin stands, 30 to 40 percent of the volume of white fir and white pine typically is rotten. In some mixed conifer stands the old aspens are almost totally useless as timber because of rot. So are some fire-scarred aspen stands. In contrast, decay usually is not extensive in ponderosa pine and Engelmann spruce.

Much windfall is partly a function of decay that has weakened roots and stems.

In Colorado more than half the decay loss in aspen is due to white trunk rot caused by *Phellinus tremulae* (Bond.) Bond. et Boris (= *Fomes igniarius* var. *populinus*), whose woody hoof-shaped conks are often seen on aspen trunks (Davidson et al. 1959). Aspens with white trunk rot often contain some sound logs, however.

Hinds (1963) has provided a guide to estimating usability of infected aspen in Colorado, based on conk locations. That guide is probably essentially valid for New Mexico and Arizona as well. Hinds and Hawksworth (1966) have also provided a guide to the recognition of decay in standing Engelmann spruce in

[9] *Southwestern populations of the western tent caterpillar were long considered a separate species,* Malacosoma fragile *(Stretch), the Great Basin tent caterpillar. A review of the genus by Stehr and Cook (1968) has placed it within the species* M. californicum *(Packard), the western tent caterpillar.*

Colorado. That guide too is probably valid for the Southwest.

Decay will be much less a factor in future mixed conifer stands because, outside of areas where visual effects are primary, few trees will be allowed to become overmature. Also, much decay in virgin stands resulted from fire scarring, which will be much less common in second-growth forests. In addition, periodic intermediate cuttings will permit salvage of injured trees before they decay extensively, and will maintain the vigor of the healthy trees that remain.

A fungal disease, Hypoxylon canker, is the most important killing disease of aspen in the Lake States (Anderson and Anderson 1969). It is widespread in the West as well (Davidson and Hinds 1956, Riffle and Hinds 1969), though less serious. It may nonetheless prove to be important in the Southwest under some conditions.[10]

Generally, in the West, Cenangium canker seems to be the most serious killing disease of aspen, and Ceratocystis cankers also do widespread damage.[11]

Fralish (1972) described how aspen overstories commonly break up in Wisconsin. Growth is vigorous in immature stands, and canopy gaps formed when trees die are rapidly filled. In mature stands, however, growth does not fill those gaps. The trees are exposed to increased sunlight, wind, and evaporation. As the stand becomes more open, these reach a point which the trees do not tolerate well and their vigor is further reduced. They become more susceptible to disease, insects, and breakage, and deterioration accelerates. Within a few years of the time the process starts accelerating, the stand may be gone.

Hypoxylon canker contributes importantly to the opening of stands in Wisconsin, and increases as the stand opens (Anderson and Anderson 1968). White trunk rot increases with age and contributes to breakage. Sunscald becomes a factor with sufficient stand opening (Hubbard 1972).

In the Rocky Mountains and Southwest, where stands may persist well past age 200, a similar process no doubt operates, albeit slowly. Breakup may well be accelerated by partial cutting.

Dwarf Mistletoe. — Dwarf mistletoes are our most difficult disease problem in mixed conifer forests. Their biology has recently been described by Hawksworth and Wiens (1972). These inconspicuous parasitic plants propagate by explosive fruits that propel seeds as much as 50 ft. The average distance is much less, however, because seeds are intercepted by foliage and so forth. Infections typically spread from infection centers at an average rate of 1 or 2 ft a year. Occasional appearances of new infection centers some distance from a source indicate an additional means of seed dispersal; birds have been suggested.

Trees newly infected with dwarf mistletoe show no external symptoms for several years. The first symptom is a swelling at the point of infection, followed quickly by small external dwarf mistletoe shoots. These can easily be overlooked when well above the ground. A few years after shoots appear, witches brooms become noticeable in most cases, and identification of infected trees becomes much easier. By that time the tree has already functioned as a source of further infection.

Dwarf mistletoe has its major impacts on the host tree after infecting the upper half of the crown. Growth then declines rapidly. Other effects include reduced seed production and lower wood quality. When infection becomes intensive enough the tree dies. Infected trees, especially Douglas-fir, become more susceptible to attack by bark beetles. In some cases the resulting brood emergence is low;[12] in other cases serious beetle buildups can result.[13]

Infections after trees have passed their years of maximum growth are less important than infections of young trees. The critical need is to keep mistletoe out of young stands so far as possible. Understories may be heavily infected from dwarf mistletoe fruiting in overstory trees. Heavy infection of an understory can result in a stand composed largely of deformed and stunted trees that are unlikely to live to maturity. This is less a prospect in mixed stands than in pure stands however, because of host specificity. Each dwarf mistletoe species in the southwestern mixed conifers has a principal host species, and normally does not parasitize

[10] *Personal communication from Thomas Hinds, Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, Fort Collins.*

[11] *See footnote 5.*

[12] *Personal communication from Melvyn Weiss, branch of pest detection and control, Southwestern Region, USDA Forest Service, Albuquerque.*

[13] *Personal communication from Frank Hawksworth, Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, Fort Collins.*

other species to any extent. If, for example, the Douglas-fir in an overstory is seriously parasitized, it will not cause infection among the spruce, pine, and white fir growing under and around it.

The most serious dwarf mistletoe in mixed conifer forests is Douglas-fir dwarf mistletoe. It occurs throughout the range of Douglas-fir in the Southwest and damages trees severely (Graham 1961). Understory Douglas-fir topped by heavily infected Douglas-fir in the overstory normally is heavily infected. Where corkbark fir grows with Douglas-fir, it too is sometimes seriously infected, but infections of other species are trivial. The external shoots of this dwarf mistletoe are often hard to find. They are very small, greenish, and often few, even on heavily infected trees. The conspicuous witches brooms are readily diagnostic, however, once they develop.

Southwestern dwarf mistletoe, sometimes called ponderosa pine dwarf mistletoe, is found almost throughout the range of ponderosa pine in the Southwest. Its biology has been examined in considerable detail by Hawksworth (1961). In mixed conifer forests its hosts are ponderosa pine, and Arizona pine in the few areas where that variety occurs in the mixtures. Trees are seriously damaged. Although witches brooms are commonly conspicuous, some heavily infected trees do not develop brooms.

This dwarf mistletoe is a less serious problem in mixed conifer management than is Douglas-fir dwarf mistletoe. While the disease is indeed very destructive of young pines, in most mixed conifer forests ponderosa pine regeneration is abundant primarily in large openings, into which infections progress slowly.

The dwarf mistletoes of other mixed conifer species are not found regionwide. Western spruce dwarf mistletoe may severely damage both blue and Engelmann spruces almost wherever they occur in Arizona outside the Chiricahua Mountains. In New Mexico, however, it is found only in the Mogollon Mountains. Its small, bristly witches brooms are often numerous on host trees, and easily distinguished from the rather shaggy, yellowish, and often large brooms, really more moplike, induced by spruce broom rust. In the large spruce and mixed conifer forests elsewhere in New Mexico and to the north, the only dwarf mistletoes on spruce are trivial crossovers from other species.

White fir dwarf mistletoe occurs in the Southwest only on the Kaibab Plateau, where it also infects associated subalpine fir. In addition to brooms, dying branches ("flagging") are a conspicuous symptom.

Southwestern white pine has two dwarf mistletoes of limited and nonoverlapping ranges, both known only on white pine. One of them, Apache dwarf mistletoe, is found abundantly and only in east central and southeastern Arizona and in central and southwestern New Mexico. It consistently causes witches brooms. The other species, *Arceuthobium blumeri* (it has no common name) occurs in the United States only in the Huachuca and Santa Rita Mountains of extreme southern Arizona. It is unique among dwarf mistletoes in the Southwest in rarely inducing witches brooms.

Dwarf mistletoes themselves are parasitized by fungal diseases, and their aerial shoots are eaten by insects and larger animals. None of these seem to provide effective natural control, although they may slow the intensification of infestations. Gill and Hawksworth (1961) suggested that damage by Douglas-fir dwarf mistletoe might be much more severe, at least in some areas, were it not for a fungus, *Wallrothiella arceuthobii.*

Forests in some habitat types are more susceptible than others to dwarf mistletoe (Daubenmire 1961). Also, dwarf mistletoe tends to be more serious on some topographic and elevational situations, although reports are not entirely consistent (Hawksworth 1959). In general, severity seems greatest on ridge tops and upper slopes, at least for southwestern dwarf mistletoe in ponderosa pine. In some locales, western spruce dwarf mistletoe occurs largely in canyon bottoms and on lower slopes, but it can be severe on other topographic situations too.

Removal of infected trees from heavily infected ponderosa pine stands will not control the infection (Heidmann 1968, Shea and Lewis 1971). Removal of enough infected overstory trees may result in blowdown of the remaining trees. In heavily infected young stands or understories, many of the trees that appear healthy and would be left are likely to have latent infections. Opening the stand typically stimulates development of shoots from latent infections, which will in turn fruit and intensify the infestation.

In mixed stands with only one species heavily infected, or where infections are moderate, such sanitation cuttings can be effective, generally favoring other species. More than a single treatment is likely to be needed, and followup should not be neglected.

Forest fires and clearcuttings have been effective sanitizers when all or nearly all infected trees were killed or cut. Natural or artificial regeneration then produces a "clean" stand that is only gradually reinvaded by the parasite.

Fire

Burning to dispose of slash is not discussed here; it will be considered later in the section on slash disposal.

More is known about fire is southwestern ponderosa pine forests than in mixed conifer forests. We will look first at the former as a partial basis for discussing the latter.

Some research and considerable historical and modern observation have provided a good picture of the role of fire in ponderosa pine forests prior to white settlement in the Southwest. The results of fire exclusion are also fairly apparent. They include severely overstocked sapling patches, reduced growth, reduced forage, and increased danger of severely destructive wildfires. The evidence has been fairly and thoroughly reviewed by Cooper (1960).

Because of the results of fire exclusion, arguments have been made for prescribed burning in ponderosa pine forests. Fuel conditions now are very different from fuel conditions that existed in the relatively open primeval forests, however. For intentional burning today, planning, skill, and care are needed because the prospects and consequences of stand destruction are substantially greater.

Pioneering tests, notably by the Bureau of Indian Affairs on the Fort Apache Reservation, have taught that "rough and ready" burning is a very crude tool both for thinning and fuel reduction, even in cool autumn weather. Under favorable conditions, when fire will burn without blowing up, it may give crude but more or less acceptable thinning on parts of the treated area. Other parts will not carry fire. On still other parts, regeneration will be largely or totally destroyed, and even some large trees scarred or killed. On parts of the area fuel accumulations will be reduced, on others untouched, and on still others increased by the addition of quantities of fire-killed saplings (Cooper 1960, Davis 1965, Gaines et al. 1958, Lindenmuth 1960).

Such variability within a burn results to a considerable extent from differences in kind and amount of fuel, in topography, and in the size and density of forest stocking. Some of it reflects weather changes while the fire is burning.

Burning as a silvicultural tool can be considerably refined. An area can be divided into subunits according to fuel, stand conditions, and other pertinent considerations. The subunits can then be burned separately when each seems likeliest to give the desired results. Locations, patterns, and rate of torching on a subunit can be adjusted as a continuous reponse to weather, fire behavior, and other on-site conditions. Although that kind of burning is more expensive, administrative studies indicate that costs can still be low — less than one 1970 dollar per acre for some jobs on large acreages (Buck 1971).

On the other hand, mechanical thinning, though expensive in precommercial stands, allows precise control of residual stocking, including selection of the trees to be retained. With present high timber values, such precise stocking control looks increasingly desirable.

The discussion so far has been restricted to ponderosa pine forests. Burning in mixed conifer forests involves some different considerations. The discussion of fire in mixed conifers is of necessity more tentative than for ponderosa pine.

Weaver (1951) dated fire scars in five pine stands. Before white settlement the average interval between fires was about 8 years. Mixed conifer forests are generally cooler and more moist than pine forests, with a litter layer typically less flammable. One would expect them to have burned less frequently than pine forests. That they did in fact burn less often is indicated by the abundance of spruce and corkbark fir of 19th Century origin and older in many mixed conifer stands. Fires in spruce-fir forests seem normally to have been holocausts at intervals of centuries.

Within mixed conifer forests the different species vary in their susceptibility to fire. For trees of pole size and larger, corkbark fir and both species of spruce are easily killed. Ponderosa pine and Douglas-fir are quite resistant. White fir, white pine, and aspen are intermediate. Seedlings of any species are readily killed. Differences in susceptibility may be important among saplings, but species order is not apparent.

Primeval wildfires were important to the composition and structure of mixed conifer forests. Most fires were light, and therefore killed many seedlings and saplings but generally spared larger trees, especially of resistant species. Patches in less flammable situations were often spared. Some patches burned intensely, especially where insects or disease left local concentrations of fuel. In such hot spots even large trees, especially of susceptible species, were scarred or killed.

Partly as a consequence, irregular structures are the rule in mixed conifer stands. Douglas-fir and ponderosa pine commonly predominate in the overstories, even where Engelmann spruce

and corkbark fir predominate in the understory. Overstory white fir and white pine often are fire scarred and defective. Groups and patches of even-aged aspen are common, many marking old hot spots.

Occasional intense fires killed almost all the trees on large areas, often leaving only scattered survivors, most commonly Douglas-fir and ponderosa pine. The subsequent succession of vegetation types is discussed in a later section.

Such severe fires do more than destroy forests. Where soils are fairly or highly erodible, severe fire may be followed by appreciable soil movement and stream sedimentation (Rich et al. 1961). Severe fires eliminate dwarf mistletoe from sites where the infected species are wiped out.

Severe fires cause high soil temperatures and can result temporarily in a strongly water-repellent layer in the soil a little below the surface, especially in sandy soils. Soil wetting is seriously inhibited while such a layer persists. Erosion is accelerated and natural regeneration delayed. Light fires burning across soils with a high clay content result in least repellency (DeBano and Rice 1971, 1973).

Prolonged fire exclusion without substitution of cultural equivalents has resulted in frequent well-developed understories of the more shade-tolerant species. Overstocking is much less a problem than in ponderosa pine stands, however, and precommercial thinning seems much less important. Given present and increasing demands, commercial thinning and salvage cutting seem to offer much better means of stocking control and regulation of heavy fuels than does prescribed burning. Prescribed fire in mixed conifer forests and aspen forests seems to have a future mainly (1) as a followup to "commerical clearcutting" where aspen dominance is to be established or perpetuated, (2) as a means of rejuvenating aspen stands for esthetic and wildlife purposes where clearcutting is not feasible, (3) as a sanitation measure following the commercial clearcutting of parts of stands where dwarf mistletoe is especially severe, (4) where an overstory predominance of ponderosa pine or Douglas-fir is to be maintained against aggressive invasion by more shade-tolerant species, (5) as a means of reducing fine fuels in stands resistant to fire under moderate burning conditions, (6) seedbed preparation during development of a cone crop after the seed cutting in the shelterwood system, and (7) as a semi-natural process in wilderness areas.

We need to know more about the effects of atmospheric conditions, fuel, and stand conditions on fire behavior, and the response of different ecosystems to fire of different intensities and duration. Such information would help us understand the potentials and limitations of prescribed burning, and allow better prescriptions.

Experienced field men have developed considerable working knowledge (Buck 1971) that needs to be summarized in print. Existing field expertise seems adequate for expanded field trials.

SOME SPECIES CHARACTERISTICS

Seed Supply

Seed supply at time of germination is a function of more than seed production. How effectively is seed distributed? How much seed is destroyed between seedfall and germination? What proportion of the germinating seedlings will establish themselves?

Based on observations, limited monitoring of cone crops, and limited seed trapping, mostly in the White Mountains of Arizona, the order of seed production by mixed conifer species seems to be approximately: blue spruce > Douglas-fir >Engelmann spruce > corkbark fir ≃ white fir > ponderosa pine ≃ white pine.

Blue spruce bears moderate to heavy cone crops in most years. Substantial Douglas-fir and Engelmann spruce cone crops are also frequent but usually lighter. Corkbark fir and white fir crops are more sporadic. Ponderosa pine crops tend to be lighter at mixed conifer elevations than lower down, and heavy crops are infrequent. In years when few or no ponderosa pine cones are found in some locales, however, significant crops are sometimes found at similar elevations nearby.

Seed production decreases when dwarf mistletoe infects the upper crown (Hawksworth and Wiens 1972).

A species bearing substantial seed crops almost yearly may take better advantage of the infrequent years when conditions for seedling establishment are especially good. On the other hand, species with infrequent good seed years may be less demanding of conditions for seedling establishment, with considerable numbers of seedlings resulting from almost any substantial seed year.

All the conifers other than white pine bear winged seed adapted to distribution by wind. White pine seeds, which are large and have vestigial wings or none at all, are distributed beyond the radius of the crown by rodents which carry seeds away and bury them. Some

such caches are not subsequently visited, and the seeds may germinate.

A moderate to heavy cone crop of all conifers in 1964 resulted in very heavy seedfall in Arizona's White Mountains. The fall of sound seed on a 10-acre clearcutting was distributed as shown by the isolines in figure 5. Within the band defined by the 400,000 isoline, seedfall averaged over 500,000 sound seeds per acre, while the area enclosed by the 40,000 isoline averaged only about 10,000 (Jones 1967b). As usual in seedfall studies, the side of the clearcutting from which the prevailing winds blow received much more seed per acre than the downwind side. Upslope sides should also receive more seed than downslope sides, and in this case the upwind and upslope sides were the same side.

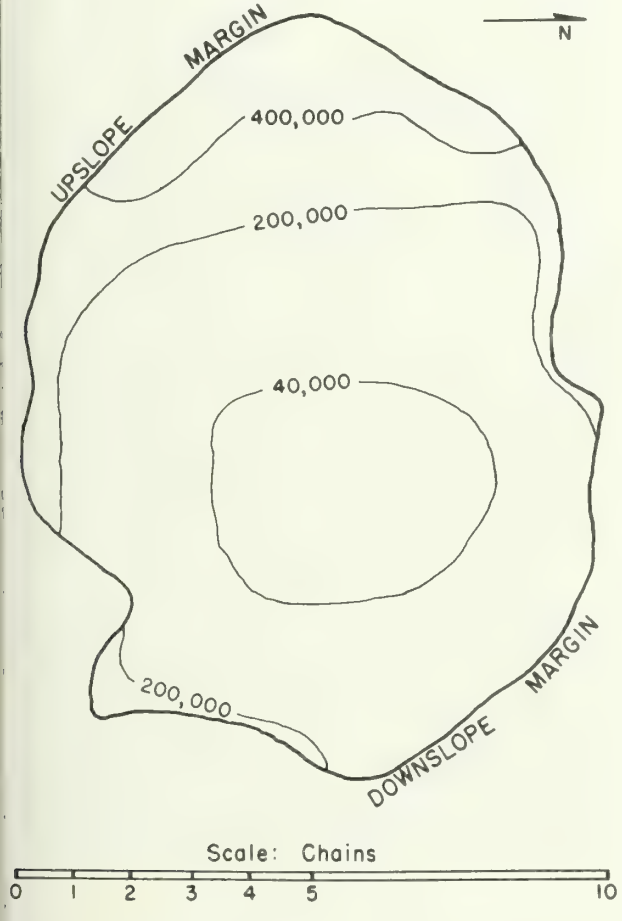

Figure 5.—The fall of sound tree seed on a 10-acre clearcutting in 1964. Very few seedlings became established, however, because of unfavorable conditions. Apache National Forest (Jones 1967b).

Mice prefer seeds of other conifers to those of true firs such as white fir and corkbark fir (Abbott 1962, Krauch 1945, Moore 1940). Some mice reject true fir seed even when extremely hungry (Abbott 1962), which no doubt helps the true firs occupy suitable regeneration sites at the expense of other species. Squirrels, on the other hand, cut and cache cones of all species in large quantities, often far beyond their ability to use them, and may take most of the healthy cones produced in years of light crops.

Aspen seed supply has not been considered because seed production seems to vary widely between pistillate clones, and because aspen regenerates almost entirely from root suckers in this region. Aspen seedlings have been reported for the West in the literature. A number were found in 1970 on the Apache National Forest, but for unknown reasons they were gone by midsummer of 1971. While aspen seedlings undoubtedly do become established under favorable conditions, current aspen regeneration significant to silviculture is by root suckering.

Germination

Germination percentages for mixed conifer species in the Southwest are available only for artificially processed seed collections. Such germination data are important for nursery and seeding practices, but are not relevant to natural regeneration. Germination test results are quite variable for processed white fir and corkbark fir seed, but usually fewer than 50 percent germinate. For the other mixed conifer species in this region, germination is rather consistently above 50 percent (USDA Forest Service 1948).

White fir and corkbark fir seed germinates in the spring on moisture from snowmelt and infrequent spring showers. No summer germination of white or corkbark firs has been observed. Stored seed sown just before or during the summer rains would probably germinate in summer, however. Some white pine seed germinates in spring, with a second period of germination after the summer rains begin. Most seed of ponderosa pine, Douglas-fir, and the spruces germinate during the summer rainy season. If significant showers fall in June, some germination of these species may begin then. June showers are more likely in southern New Mexico than elsewhere in the region.

Ponderosa pine germination on mixed conifer sites may continue well into September, and August germination is common. Late germination results in seedlings with relatively shallow

root systems at the end of the first growing season — seedlings which are more susceptible to frost heaving and drought than earlier germinants (Larson 1961). It is not known whether such late germination is as common among the other summer-germinating species. A minor amount of mixed conifer seed that does not germinate the first growing season after seedfall may germinate the second summer.

Aspen Suckering

Aspen stands have a network of interconnected lateral roots (Barnes 1966, DeByle 1964, Gifford 1966). Aspen regenerates by sprouting (suckering) from shallow roots, using food stored in them. Increased root temperature caused by exposure of the soil to sunlight is a cardinal factor in stimulating suckering (Maini and Horton 1966).

When an aspen stand is burned or clearcut, sucker density after the first full growing season is likely to be in the tens of thousands per acre (Baker 1918, 1925; Larson 1959; Smith et al. 1972). Also where aspens were fairly numerous in mixed conifer stands, clearcutting or severe fire has resulted in abundant suckering. In the Lake States, disking has increased initial suckering, but subsequent poor survival and growth have been reported (Perala 1972). Initial sucker density may vary with season of cutting, but the difference decreases with time (Baker 1925, Graham et al. 1963, Sandberg and Schneider 1953) and does not seem important in the Southwest.

In partially cut stands, the remaining overstory aspens shade both the ground and the sucker stand. Also, aspen shows strong apical dominance, at least in young trees (Farmer 1962, Schier 1972). Presumably, then, residual aspens inhibit suckering and sucker growth by shading, by chemical inhibitors, and by priority use of food stored in the parent root system. While initial suckering is sometimes more than adequate following partial cutting, survival and growth are unsatisfactory (Baker 1918, 1925; Farmer 1962; Larson 1959; Pearson 1914; Sandberg and Schneider 1953; Schier 1972; Smith et al. 1972; Stoeckeler and Macon 1956; Zehngraff 1947, 1949).

Early Growth

Studies of juvenile mixed conifer growth rates have been few. A recent Arizona study of limited scope (Jones 1971) gives a picture that agrees in essentials with the limited New Mexico data of Krauch (1956) and Miller.[14] Growth in the shade is slower than in the open. Five-yr-old Engelmann spruce and corkbark fir under a small gap in the crown canopy received little direct sunlight. They averaged only 3 inches tall and showed no sign of accelerating with age. That average is quite in line with findings for those species in other parts of the interior West from Canada southward.

In a larger gap, where seedlings received continuous direct sunlight for 1 to 2 hours daily, 5-yr-old Douglas-fir, Engelmann spruce, and corkbark fir still averaged only about 5 inches tall but their growth had started to speed up.

Although early survival of most species tends to be very poor in the open, those seedlings surviving the sensitive first 2 years or so normally grow much faster than shaded seedlings if competition for moisture is not severe. Six growing seasons after germination on a clearcutting, most ponderosa pines were taller than 25 inches, most Douglas-firs were taller than 20 inches, and Engelmann spruces averaged 15 inches. That species order of growth rates probably would not hold on all mixed conifer clearcuttings. Seedlings of other species were too few for meaningful measurements. Growth was accelerating in all species. Observations suggest these were superior growth rates for mixed conifer clearcuttings, perhaps because of the unusually sparse herbaceous competition. Seedlings were also unusually numerous for a clearcutting.

A large number of Engelmann spruce seedlings suppressed beneath a mixed conifer canopy were partially released by heavy selective cutting in late 1957. They then averaged 7 inches tall. Growing in considerably increased light they reached an average of 77 inches by late 1969 and 92 inches a year later.

Aspen suckers in the open grow much faster than coniferous seedlings. Extensive sampling in Colorado, northern New Mexico, and eastern Arizona showed that most aspen suckers reach breast height within 2 to 5 years. A few reach breast height during their first growing season (Jones 1967a).

Less is known about early root growth than about shoot growth. Our limited information on root growth is from naturally established seedlings growing in silt loams and silty clay loams in Arizona's White Mountains (Jones 1971). The following tabulation gives root

[14] *Miller, F. H. 1923. Growth and yield for the important timber species in northern New Mexico. (Unpublished report in the files of the Rocky Mountain Forest and Range Experiment Station, Flagstaff, Arizona. 61 p.)*

penetration in inches after one and five growing seasons for the four species found in large numbers.

Species	1 yr	5 yr
	(Inches)	
White fir	7½	10
Douglas-fir	3	8
Corkbark fir	3½	6
Engelmann spruce	2½	6

The roots of all species were much more abundantly branched after five growing seasons than after the first (fig. 6). All seedlings were growing in considerable shade. The 1-yr-old white fir were shaded least — about half the day. If 5-yr-olds had been found in clearcuttings they probably would have been found to root more deeply. Rooting might also have been deeper in sandier soil.

Figure 6.—Representative corkbark fir seedlings after 1 to 6 growing seasons. There is no second-year seedling (Jones 1971).

A few root systems of white pine and ponderosa pine were also examined. Seedlings of both species germinating fairly early in the rainy season seem to penetrate about as deeply the first year as white fir, but white pine roots, at least, penetrate much more deeply than white fir during the subsequent few years.

Later Growth

Our coniferous species grow much faster in the sapling and pole stages than as seedlings. The only pictures we have of growth beyond the seedling stage are given by site index curves.

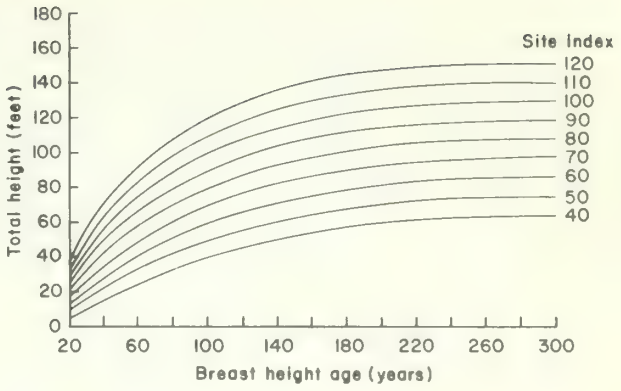

Figure 7.—Site index curves for Engelmann spruce in Colorado and Wyoming. Base age 100 yr after reaching breast height (Alexander 1967a).

Alexander's (1967a) curves for Engelmann spruce in Colorado and Wyoming (fig. 7) seem reasonable representations of Engelmann spruce height growth in New Mexico and Arizona. The ages shown are not total ages, but breast height ages. Thus the curves represent heights at the indicated number of years after the tree reached breast height, which is after the period of very inconsistent and often very slow juvenile growth has ended. Brickell's (1966) site index curves for Engelmann spruce in the northern and central Rocky Mountains should not be used in the Southwest. Their forms do not at all represent growth in this region, and grossly overstate juvenile growth for all Southwestern sites. Therefore they greatly underestimate site index when young stands are used and seriously overestimate it when mature stands are used.

Walter Meyer's ponderosa pine site index curves do not, Meyer wrote, satisfactorily represent the species in the Southwest (Meyer 1938). Minor's (1964) curves, on the other hand, were developed explicitly for ponderosa pine in Arizona (fig. 8), and while based on data from the ponderosa pine zone they probably are reasonably appropriate for ponderosa pine on mixed conifer sites. Like Alexander, Minor used breast height age instead of total age.

Jones (1967a) developed site index curves for aspen (fig. 9), available also as a table (Jones 1966). Again breast height age was used.

There are not site index curves suitable for the other mixed conifer species in the Southwest. Until some have been developed, Alexander's (1967a) curves for Engelmann spruce can be used for Douglas-fir, white fir, corkbark fir, and blue spruce with the understanding that accuracy is very likely poor. Minor's (1964) curves

for ponderosa pine can be used for white pine with the same reservation. Brickell's (1968) site index curves for Rocky Mountain Douglas-fir should not be used in the Southwest for the same reasons his Engelmann spruce curves should not: they are grossly inaccurate for this region.

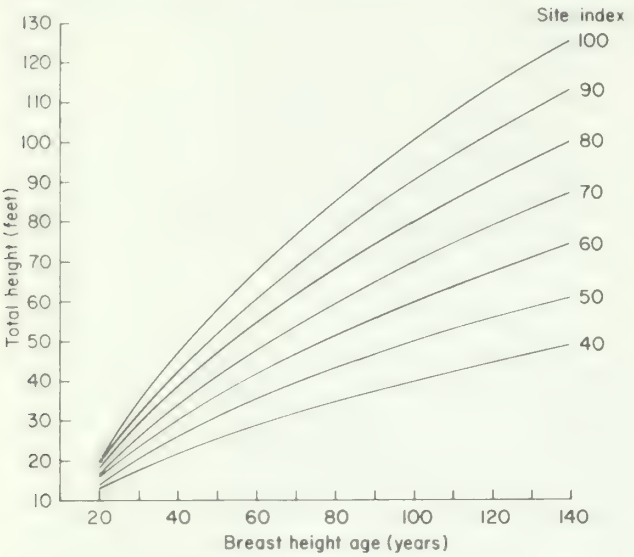

Figure 8.—Site index curves for young-growth ponderosa pine in northern Arizona. Base age 100 yr after reaching breast height (Minor 1964)

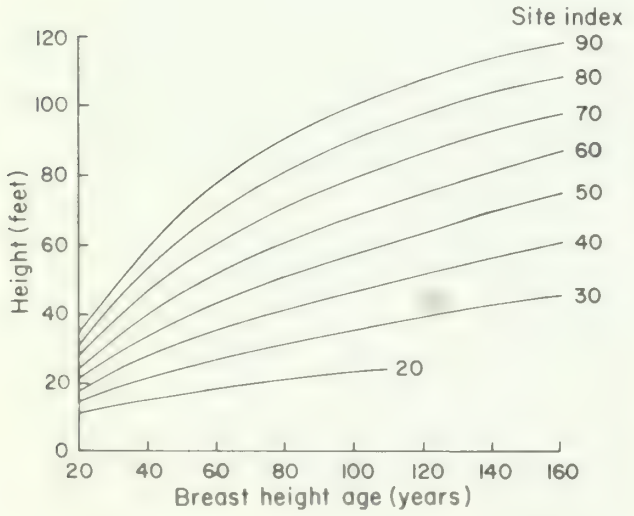

Figure 9.—Site index curves for aspen in the southern Rocky Mountains. Base age 80 yr after reaching breast height (Jones 1967a).

Sample trees from saplings to veterans were measured on 1,800 acres of virgin mixed conifer forest in Arizona's White Mountains (Embry and Gottfried 1971). The largest measurements (below) are not uncommon for the better trees on good Southwestern sites:

Species	Greatest — Height (ft)	d.b.h. (in)
Douglas-fir	148	51
Ponderosa pine	145	40
White fir	134	49
White pine	130	44
Engelmann spruce	125	36
Corkbark fir	125	34
Blue spruce	124	26
Aspen	110	26

These are all large trees by Southwestern standards, but none is really exceptional.

An exceptionally fast-growing Engelmann spruce at 9,300 ft in eastern Arizona reached 18 ft 9 inches 24 summers after germinating. It then added 29 ft 10 inches in just 11 yr for a height of 48 ft 7 inches at a total age (not a breast height age) of 35.

Examples of outstanding sizes for the Southwest are an Engelmann spruce 45 inches d.b.h. and 160 ft tall (fig. 10) and a 72-inch d.b.h. Douglas-fir that measured 150 ft to a broken top. Douglas-fir 160 ft tall occasionally are measured.

Figure 10.—An Engelmann spruce 45 inches d.b.h. and 160 ft tall stands in approximate center of photo. San Juan National Forest.

Shade Tolerance

Observation and limited study (Jones 1971) suggests the following species order of shade tolerance in the Southwest: Engelmann spruce $\simeq$ corkbark fir $>$ white fir $>$ Douglas-fir $\geq$ blue spruce $>$ white pine $>$ ponderosa pine $\geq$ aspen. The criteria used were ability of seedlings (or suckers) to continue healthy, if slow, growth in shade; and ability of shade-suppressed seedlings to accelerate growth when light was increased.

Light Tolerance

Light damage to seedlings growing in the open was discussed under the section on light. Limited data on very small outplanted seedlings indicated corkbark fir was extremely susceptible to light damage when unshaded, even though watered. Douglas-fir was highly susceptible. Engelmann spruce and white fir seemed quite susceptible, but apparently less than Douglas-fir. None of those four species seem suited to prompt regeneration of large bare areas from seed unless shade is provided.

Ponderosa pine and white pine are relatively resistant to damage by full sunlight, but benefit from shade in severe situations.

Blue spruce shows a tendency to invade the edges of openings, suggesting good light tolerance, but study results are ambiguous.

SUCCESSIONS AND CLIMAXES

In the absence of severe redisturbance on deforested mixed conifer land, several biotic communities are likely to succeed one another, each modifying the microenvironment in ways that favor its replacement by another community. Prolonged absence of disturbance will result in a climax community that tends to persist on the site until severe disturbance such as fire changes it.

Because the composition of the climax community is a function of various interacting habitat factors, the potential climax community for a site can be used to characterize the habitat (Cajander 1926, Daubenmire and Daubenmire 1968). The sequence of successional communities that follows a major disturbance is partly a function of habitat; partly of the nature, severity, and size of the disturbance; and partly of subsequent events such as the kind, amount, and timing of seedfall.

In forests managed for timber production, frequent light harvests that remove scattered individuals favor development and maintenance of a near-climax community. To maintain the forest in an early successional stage may be difficult, and ordinarily requires the removal of trees in substantial groups to make large gaps in the canopy. To maintain a ponderosa pine forest on a mixed conifer site, for example, may require clearcutting (including understory removal) and planting.

Figure 11 is a diagram of natural forest successions on mixed conifer and spruce-fir sites after complete forest removal. It is partly speculative, and some successions may conceivably have been overlooked. The communities are designated by the predominant plants or life forms.

If a grass-pocket gopher-vole community or oak scrub becomes dominant on a mixed conifer or spruce-fir site, conifers may be largely excluded for decades — in some cases more than a century — unless the site is reforested artificially.

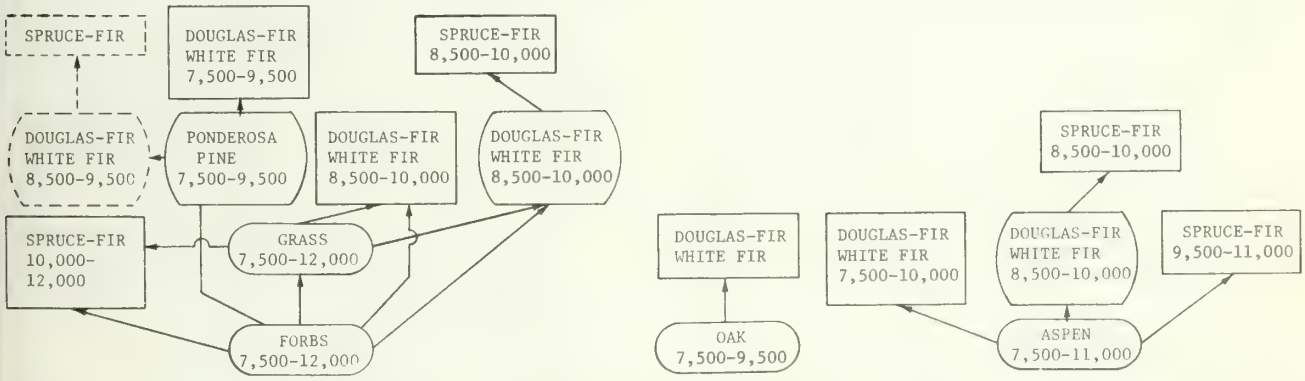

Figure 11.—Mixed conifer and spruce-fir forest successions in the Southwest. Broken lines indicate speculative successions. Numbers are approximate elevations. Community types are labeled according to characteristic dominants.

Successional trends in many spruce-fir stands in the Northern Rocky Mountains indicate strong climax dominance by subalpine fir (Daubenmire and Daubenmire 1968). There is little evidence that this is true of corkbark fir in the Southwest, however. Spruce beetle outbreaks may result in dominance by corkbark fir for a time, but observation indicates that Engelmann spruce regains an important overstory role.

If an aspen stand becomes established following burning or clearcutting of mixed conifers, a coniferous understory is likely to become established within a few decades — sometimes within a single decade — where suitable seed is at hand. Aspen dominance is likely to last for 100 to 200 yr however — until the understory grows through it or the aspen dies.

If adequate coniferous seed is not available for invasion, aspen will maintain dominance, for a time at least, by replacing itself through suckering, even without burning or clearcutting.

In Colorado, Utah, and Wyoming, many aspen stands show no sign of significant coniferous invasion even with a seed source nearby. DeByle has questioned whether aspen can maintain itself on such sites indefinitely without fire or clearcutting, or whether it would eventually be displaced by grass and shrubs.[15] His point is well taken. The somewhat uneven-aged sapling stands that become established during overstory deterioration are certainly much more open and less vigorous than the even-aged stands which follow fire or clearcutting, and may prove unable to replace themselves later.

ECOSYSTEM CLASSIFICATION

Ecosystem classification was recently examined in detail in a Forest Service task force analysis.[16]

It commonly is difficult to generalize the results of experience, observation, and research in mixed conifer silviculture and ecology. A management practice proven successful in a few cases is likely to fail in others. In some cases it may succeed but amount to management overkill — it may be considerably more expensive than necessary for the given set of circumstances. Even the objective of a practice will likely be unrealistic or otherwise inappropriate to some circumstances in which it is applied. These things happen because ecosystems are complex physical-biological systems that differ from place to place and time to time. Inputs differ in different ecosystems, they are processed somewhat differently, and they have different outputs.

The purpose of ecosystem classification in forestry is to define which ecosystems respond similarly to given treatments or other events. The differences and similarities that seem important to how ecosystems behave and respond, or that reflect how they behave and respond, are the basis for ecosystem classification.

Characteristics that differ from one ecosystem to another can be fitted into several categories:

1. The essentially permanent habitat features such as climate, terrain and soil, whose biologically effective interactions are reflected to a considerable degree in the composition of the climax vegetation. For silvicultural purposes, classification of those features is commonly into **habitat** types based on climax vegetation.
2. The existing community of plants and animals, the biological assemblage on the site at a point in time. It may or may not resemble the climax community. It has a composition, a structure, and a condition. It modifies the physical environment provided by the permanent habitat features, and it responds to treatments and other events. The environment on a site is much different if that site is occupied by a dense stand of aspen saplings than if it bore an open meadow. It will be different still when the aspens reach maturity, especially if an understory of conifers has developed. A well-stocked stand of Douglas-fir poles on the site results in another quite different environment. That environment will have changed substantially by the time the stand has aged and the one-time poles have become an open overstory of scattered old veterans, many of them decadent or infected with dwarf mistletoe. Effects and responses of the existing community can be dealt with within the framework of a **stand classification.** In practical stand classification it is probably best to exclude consideration of erratic transient community elements such as outbreak populations of insects.
3. Temporary nonnormal conditions, notably unusual drought, nonnormal seed availability, or exceptional biological pressures such as insect epidemics. It is doubtful that these

[15] *Personal communication from Norbert DeByle, Intermountain Forest and Range Experiment Station, USDA Forest Service, Ogden.*

[16] *ECOCLASS, a method for classifying ecosystems, a task force analysis. Draft submitted to the Chief, USDA Forest Service, on Jan. 18, 1973.*

can be dealt with in ecosystem classification, although they are important considerations in forest management.

Those three categories are fairly inclusive insofar as natural terrestrial ecosystems and their processes are concerned. But some ecosystems are aquatic. And a treatment applied only to a terrestrial ecosystem may nonetheless have important effects on streamflow, sediment load, the kinds and concentrations of solutes in the stream, and so forth, with consequences to fisheries, water supply for wildlife and livestock, and downstream uses.

Also, forests experience nonnatural processes induced by man. A habitat type may sometimes occur on different geological-topographical situations in which the total biological behavior is closely similar, but which may respond differently to traffic, water flow, and other factors. They may require different standards of road construction and maintenance, different logging equipment, different seasons of logging, and may impose different constraints on silvicultural methods.

Thus two more categories of ecosystem characteristics need to be added to the three already discussed. They are:

4. Characteristics of land considered purely as a physical system, not as a physical-biological response system. Those characteristics can be dealt with by what has been called a **land system classification.**
5. The components of an **aquatic system.** A stream or lake integrates responses to elements of all the preceding categories; it responds to all the terrestrial ecosystems of its drainage.

A complete ecosystem classification for forest management would consist of separate classifications defining habitat types, stand types, land systems, and aquatic systems. Four separate classifications do not amount to duplication. Each looks at a different aspect of the total ecosystem, to fill the total management need. Together they can provide a fairly precise framework for relating effects to their causes, or at least to the conditions in which they can be expected. They would enable us to learn much more effectively from our research efforts, our observations, and our management experiences. Predictions and treatment prescriptions would become more reliable and more efficient. Planning would be more effective.

The four constituent classifications can be made independently, although some of the same factors must be considered in all of them. Any one of them can be used alone if the others aren't ready for use. All would be subject to refinement based on use and further research. Development of a fully satisfactory stand classification may well require a habitat type classification as a prerequisite, however, and a fully satisfactory classification of aquatic systems may require that classifications of habitat types, stand, and land systems be available.

The Forest Service established a task force to develop an ecosystem classification for the northwest — Washington, Oregon, Idaho, Montana, and Wyoming. That classification is to serve as a prototype for development of classifications elsewhere in the country. The task force analysis looked primarily at habitat type classification, land system classification, and aquatic system classification. Development and evaluation of habitat type classifications for different parts of that region is well advanced (Daubenmire 1952, 1961; Daubenmire and Daubenmire 1968; Driscoll 1964; Franklin and Dyrness 1973; Pfister et al. 1972; Reed 1969), and seems to have established the practicality of the habitat type approach.

No habitat type classification is yet available for the Southwest. The Southwestern Regional Office of the Forest Service has, however, contracted for a reconnaissance classification of mixed conifer habitats on four southwestern National Forests as a first step. The present "land sensitivity" classification for land use planning in Southwestern National Forests is a partial first-approximation land system classification.

The Soils Branch of the Regional Office has classified and mapped the soils on a considerable portion of the Southwestern National Forests. That work will be useful in developing and refining habitat types, and especially useful in classifying the land system.

A partial first-approximation stand classification for southwestern mixed conifer forests is presented in the next section as a framework for discussing silvicultural treatments.

STAND STRUCTURES

Alexander (1973) classified the stand structures of old-growth spruce-fir forests as single-storied, two-storied, three-storied, and multi-storied. His classification is readily adapted to mixed conifer forests (fig. 12). In the descriptions that follow, advance regeneration less than 4.5 ft tall is not considered to constitute a story.

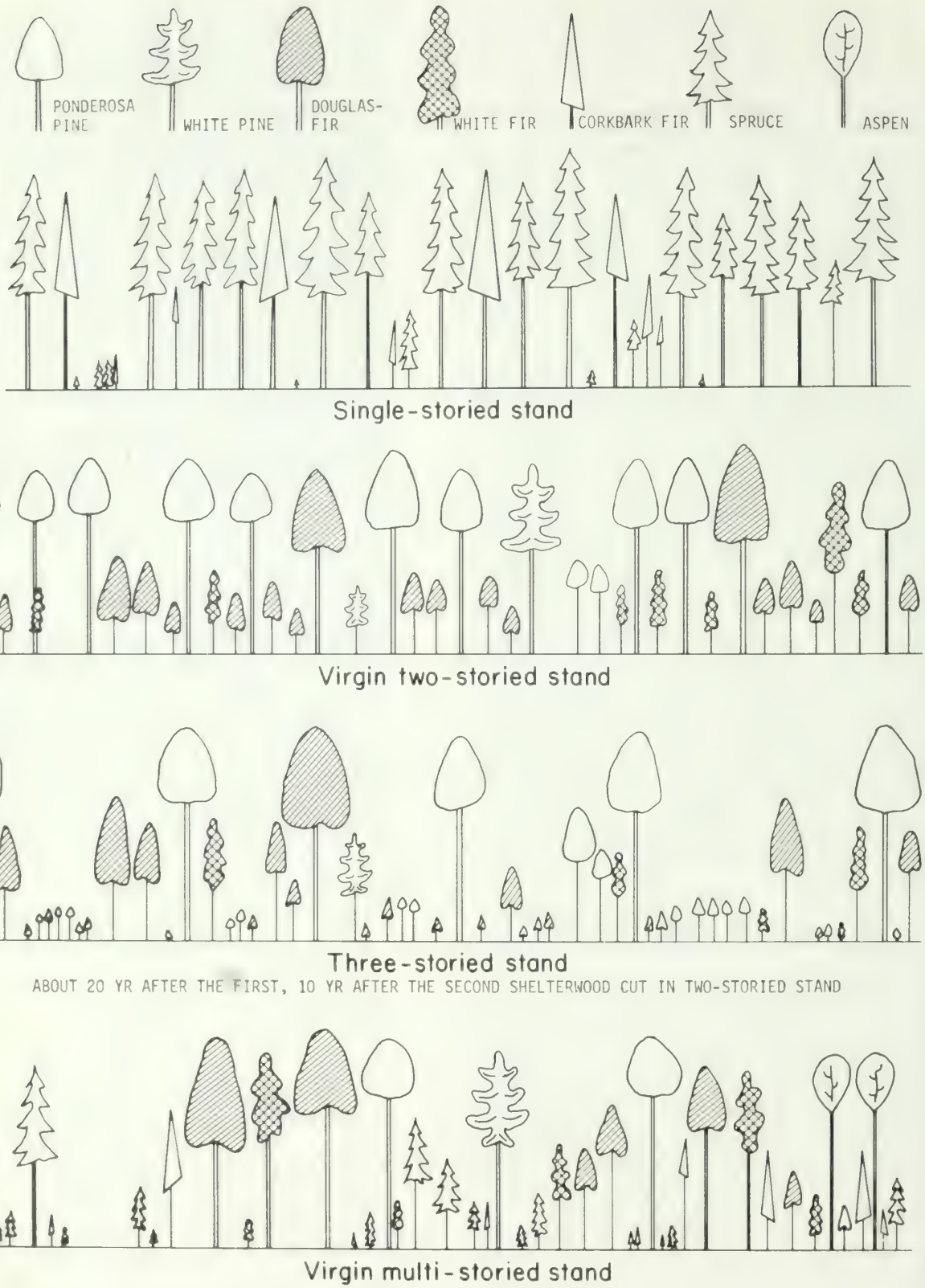

Figure 12.—Transect profiles of stand structures. The species shown represent frequent compositions.

Single-Storied Stands

A single-storied structure is uncommon in mixed conifer forests. It is more frequent in spruce-fir and aspen forests. Single-storied stands have the following characteristics:

1. The stands may appear even-aged but often contain more than one age class. Single-storied aspen stands usually are even-aged.
2. Numerous trees may be 5 to 10 ft taller than the general canopy level, with occasional trees 15 or 20 ft taller. Some trees may be entirely below the canopy, but are too few and too unhealthy to constitute a second story; they are likely to be as old as many canopy trees.
3. A manageable stand of advance regeneration is usually absent.[17] Vigorous advance regeneration is likely to be found mainly beneath scattered canopy gaps where old trees have fallen or died.
4. The canopy is usually rather uniformly stocked.

Two-Storied Stands

Two-storied stands may contain more than two age classes. The overstory is likely to be predominantly ponderosa pine or aspen, with an understory mostly of other species (fig. 13). Aspen stands in the Southwest are often two-storied, with the overstory almost entirely of aspen and the understory of mixed conifers or spruce-fir (usually with few or no ponderosa pine) (fig. 14). The overstory is likely to be rather uniformly stocked.

Three-Storied Stands

Some three-storied mixed conifer stands have resulted from harvesting in two-storied stands. The overstory has been partly removed, and logging has created numerous openings in the second story which have restocked.

Other three-storied stands result from overstory deterioration in two-storied stands. In the latter case the upper story is likely to be rather decadent, and the second story of poles and small sawtimber mostly of shade-tolerant species.

There may be substantial patches with moderate to heavy dwarf mistletoe infection.

[17] *Because even careful harvesting will destroy some advance regeneration, a manageable stand of advance regeneration should consist of at least 600 well-distributed seedlings and saplings per acre with good form and in good condition.*

Figure 13.—A two-storied stand. Overstory is almost entirely ponderosa pine; understory is mostly Douglas-fir, with some white fir, white pine, and ponderosa pine. Apache National Forest.

Figure 14.—A two-storied stand. Overstory is 150-yr-old aspen; understory is mostly Douglas-fir and Engelmann spruce. Apache National Forest.

Multi-Storied Stands

Multi-storied stands are common. Their oldest trees are likely to be remnants of what was once, centuries ago, an understory beneath an aspen canopy, or of a single-storied stand that seeded in after a severe fire. The irregular structure of a multi-storied stand is likely to have resulted from the irregular decimation of the older age classes, over time, by lightning, wind, insects, diseases, and more recently by selective cutting. The resulting openings regenerated more or less as they occurred.

Such stands (fig. 15) are likely to consist of a mosaic of groups and patches quite variable in area. Some of the patches may be single-storied, some two- or three-storied, and others multi-storied, but the overall effect is of a multi-storied stand.

Figure 15.—Virgin multi-storied stand. Apache National Forest.

Some other structural characteristics are:

1. Trees are generally of many sizes and ages.
2. In virgin stands the oldest age class is likely to be of very old trees, many occurring in groups. While many may be sound, many others may be seriously decayed or spike-topped, and dwarf mistletoe may be abundant.
3. In stands that have been selectively cut, the oldest age class is likely to be mostly of sound trees without a strong tendency to occur in groups.
4. Ponderosa pine may be numerous among the oldest trees, but is usually much less frequent, or may even be absent, among younger classes.
5. Douglas-fir commonly predominates among the older trees, but among pole and sapling classes often is outnumbered by white fir. In some stands both Douglas-fir and white fir are largely replaced in the sapling class by Engelmann spruce and corkbark fir.

Understocked Stands

Even after a number of years, occasional heavily cut stands have not restocked to the point that "stories" are evident. Occasional virgin stands consist only of individuals and groups in a matrix of grass. Several age classes are likely to be present in these virgin stands, but with no evidence of a strong approach toward full stocking. In the cutover stands much of the stocking is likely to be of mature trees, with regeneration deficient.

SILVICULTURE

Silviculture is an effort to manage forests by influencing ecological processes. The objectives are production of wood, water, forage, and recreational opportunities, and the maintenance of wilderness — singly or in various combinations. At different times and places one or more of these objectives will have limited compatibility with others.

The following discussion is of silvicultural methods primarily for growing timber. While many of the same principles and methods apply to the production of other values, they will sometimes differ to some degree from those discussed here.

Silvicultural methods will be discussed under two headings: reproduction methods and intermediate treatments.

Reproduction Methods

Harvesting is the major reproduction tool. It not only converts trees to useful wood products, it also modifies the environment on the site — may change it strongly if enough trees are removed. The purpose is to provide an environment suited to the establishment and growth of new trees.

In most humid temperate climates, nature will replace a forest without help, but she may take a long time and the result may not be satisfactory from a social or economic point of view. Planting and artificial seeding can often speed reforestation and give better control of the composition and structure of the new stand.

Methods and frequencies of stand treatment should be fitted to the needs of site, stand, and objectives. Discussion of reproduction cutting will be organized largely according to stand structure and composition. Artificial reproduction will be discussed in a separate subsection.

Methods of regenerating spruce-fir forests, as defined on page 1, will not be specifically discussed here, although much that is included here is pertinent to spruce-fir stands. For specific discussions of the silviculture of spruce-fir forests, see Alexander (1973, 1974), and Roe et al. (1970).

SINGLE-STORIED STANDS

Aspen

Much of what is written here is adapted from extensive research and timber management in the Lake States and Canada, modified by observation and research in the West. Convenient major collections of aspen information from northern forests are the proceedings of a recent symposium (USDA Forest Service 1972), and the monograph by Graham et al. (1963). Baker's small monograph (1925) on western aspen is dated but still very useful.

Timber consumption trends suggest that the lumber and fiber potential of western aspen forests will be important in the future. Right now, however, not all locales have a market for aspen logs. The presence or absence of markets strongly conditions what can be done.

Where a market exists for small products such as pulpwood, it may be feasible to harvest almost all the trees. The remainder should be felled during logging or immediately afterward to stimulate abundant vigorous aspen sprouting. Ordinarily that should be all that is necessary for satisfactory regeneration.

If the acreage of aspen cut is small, aspen regeneration may be eliminated by browsing unless protected for the first 2 to 4 years. Cutting fairly large acreages as a single large unit or as several nearby units should reduce browsing pressure.

If a market exists only for saw logs, clearcutting may not be feasible. Residual aspens are very susceptible to windthrow where a mature stand has been opened excessively, and disease may also become severe (Anderson and Anderson 1968). If clearcutting is not feasible, up to 30 percent of the basal area can be marked for removal on an individual tree basis. Group selection may result in sunscald on the north side of the openings (Hubbard 1972). Cutting 20 or 30 percent will not constitute effective regeneration cutting, but the rest of the stand is likely to remain intact for a time and may make good growth (Martin 1965).

An alternative is to cut all merchantable trees, let the unlopped slash cure in place, and broadcast burn during the dormant season. The fire should kill many of the residual trees and stimulate suckering. Burning in autumn, when the cured herbaceous cover is still upright, may work best in the Southwest, where fall is often dry. Concentrating slash around residual trees before burning may give a better kill.

Conifer seedlings grow much more slowly than aspen suckers. There are sites occupied by aspen, however, where conifers will produce more wood per acre per year over the course of time than will aspen. Conversion to conifers may therefore be desirable. Because we are talking about single-storied stands — those without a coniferous understory — planting or seeding shade-tolerant conifers is necessary for conversion.

Shade-tolerant conifers can be planted either before or after the stand is logged. Observation in the Lake States suggests that a heavy stand of suckers constitutes more difficult competition to conifer seedlings than does a mature or overmature aspen stand. Therefore, if planting is to follow cutting, about 60 ft^2 of basal area in aspen canopy trees could be left to suppress suckering (Waldron 1966).

If planting follows partial cutting, the conifers will develop better if the residual aspens are cut or killed when the plantation is about 8 to 10 ft tall (Lees 1966, Steneker 1967). Plantation-release logging of aspen on thousands of acres in Wisconsin has demonstrated repeatedly that, with explicit protective clauses in timber sale contracts, and effective sale administration, plantations can be released by commercial logging without excessive damage to the planted trees. Release by spraying the aspen with chemical herbicides in late summer is economical and effective, but may be controversial.

If the aspen is to be clearcut or nearly clearcut before planting, provision should be made to release the conifers from the resulting suckers two or more times.

Artificial seeding has proved very unreliable for establishing conifers beneath an aspen stand. First-year seedlings in particular suffer heavy losses to burial by aspen leaves and herbaceous growth. Natural establishment of conifers beneath aspen ordinarily results from repeated seedfall over a period of years. If seeding is to be tried, mineral soil seedspots should be made close to the north sides of aspen trunks (Waldron 1961), and plans should be made to repeat the seeding in following years.

Where no aspen market exists, options are limited. If serious deterioration has not begun, the stand can be held untouched for a future market. Ordinarily this maintains the esthetics of aspen but foregoes some other possible benefits.

Decadent stands can be replaced with new sucker stands by a hot burn. In the process, forage for deer, elk, and livestock is greatly increased for several years (Patton and Avant 1970). Water yields should also increase for several years (Johnston et al. 1969). The resulting fire-killed snags might be esthetically undesirable for some areas.

Ordinarily, aspen stands are not very flammable. Burning them requires readiness to act promptly on the occasions when they will, in fact, burn effectively.

Felling the aspen instead of burning provides comparable benefits without creating a stand of snags, but at considerably greater cost. The branchy tops can be lopped after felling to allow game and livestock freer movement, or left unlopped to protect the suckers.

After a few years, water and forage yields on burned or logged aspen areas decrease to pretreatment levels as the sucker stand grows (Johnston et al. 1969, Patton and Avant 1970). Increased water yields can be retained, however, if the aspen type is converted to grassland. An area could likely be converted by burning or by clear-felling and lopping, followed by 3 yr of heavy summerlong use by sheep. The area then could be seeded with grass if necessary.

Conifers

Alexander (1973) discussed and made recommendations for partial cutting in single-storied spruce-fir stands. His ideas (indented below) form the basis of our discussion here. Windfall risks are defined on page 5.

> Single-storied stands are usually the least windfirm because the trees have developed together over a long period of time and mutually protect each other from the wind.
>
> 1. **If the windfall risk is below average, and the trees are uniformly spaced,** the first cut should be light, removing about 30 percent of the basal area of the stand on an individual tree basis. Since all overstory trees are about equally susceptible to windthrow, the general level of the canopy should be maintained by removing some trees from each overstory crown class. Avoid creating openings in the canopy with a diameter larger than one tree height by distributing the cut over the entire area.

The subsequent cut should probably follow after 5 to 10 yr and remove a volume similar to the first cut. A third cut should not be made until the regeneration stand is well established. The third cut might remove all the remaining overstory trees, or part of them might be held for a fourth cut to provide an additional period of protection for the regeneration and to fill gaps in the regeneration caused by the third cut.

> 2. **If the windfall risk is below average and the trees are clumpy,** the first cut should be a modified group selection that removes about 30 percent of the basal area. Harvesting timber in groups will take advantage of the natural arrangement of trees in clumps. Group openings should be kept small — not more than one or at the most two tree heights in diameter — and not more than one-third of the area should be cutover.

Subsequent cuts probably should consist of enlarging the openings after they have regenerated by cutting adjacent clumps. If the clumps amount to patches larger than about 1.5 tree heights in diameter, ignore the clumpiness and mark individual trees as in item 1 above.

> 3. **If the windfall risk is above average,** the first cut should remove about 10 percent of the basal area on an individual tree basis, regardless of the spacing between trees. The objective is to open up the stand just enough to allow the remaining trees to begin to develop windfirmness. This type of cutting resembles a sanitation cut in that the poorest risk trees (and super-dominants) should be removed, but it is important that the general level of the overstory canopy be maintained intact. If the stand is clumpy, try to leave the clumps intact. Provision should be made to salvage windfalls.

Two additional light cuts at 5- to 10-yr intervals should condition the stand for treatments like those described in items 1 and 2 above.

> 4. **If the windfall hazard is very high,** or the stand is breaking up, the choice is usually limited to removing all the trees or leaving the area uncut.

If the stand is clearcut, planting will generally be necessary to regenerate it within an acceptable time, unless an aspen sucker stand develops.

In the Southwest, **dwarf mistletoe must also be considered.** Single-storied stands are likely to be strongly dominated by a single

species. If that single species is heavily infected, controlling dwarf mistletoe by harvesting all infected trees in one operation may be too drastic.

Cutting should remove as many recognizably infected trees as possible while still considering windfirmness. If infected trees remain for the final removal cut because the stand had been heavily infected, the final removal should be made no later than 20 yr after the first substantial wave of seedling establishment. The regeneration stand should be sanitized promptly after final removal of infected trees. The regeneration should be reexamined a few years later because a second sanitation is likely to be necessary. A third may be needed after a few years.

Seed production of a heavily infected species may sometimes be so poor that artificial regeneration will be needed if that species is to be retained as an important stand constituent. The ground should be examined for evidence of recent substantial cone crops.

TWO-STORIED STANDS

Ponderosa Pine Overstories

A mixed conifer understory beneath a predominantly ponderosa pine overstory may be rather well stocked and healthy. In that case the reproduction method amounts essentially to the removal cuts of the shelterwood system. Special care (described later) should be used to minimize damage to the understory.

Where the understory is well stocked and primarily of healthy saplings and well-established seedlings, the overstory may be removed in a single carefully planned and controlled cutting. From three to five removal cuts at intervals of 5 to 10 yr can reduce logging damage, however. In that case the first cut should remove no more than 30 percent of the overstory basal area as selected individual trees, to avoid blowdown. If the windfall hazard is greater than average, the initial cut should remove either all the overstory or else not more than 10 to 20 percent of it. The number of log landings for overstory removals is likely to exceed that necessary for intermediate treatments in the new stand. Landings, or parts of landings, to be retained as work openings or wildlife openings should be planted promptly after logging with forage species. Others normally should be planted or seeded to trees. Unless heavy browsing is anticipated, ponderosa pine is an appropriate planting species.

If the understory contains many pole-sized trees or is poorly stocked, the overstory should ordinarily be removed in several installments. Understory trees 4 inches or larger in diameter seem especially susceptible to blowdown if the protection of overstory trees is removed abruptly.

Where the windfall hazard is average, the first cut should remove about 30 percent of the overstory basal area as selected individual trees. A second harvest 5 or 6 yr later would remove about 40 percent of the remainder. The rest of the overstory would be removed in one or two additional cuts over a period of 10 or 15 yr. That should permit the pole-sized trees to develop windfirmness and avoid serious blowdown of overstory pines pending final removal.

In most cases, poorly stocked places should fill in naturally before the final cut. Landings and other disturbed places should be planted promptly after the final removal, with timber or forage species, depending on whether or not the opening is to be retained.

Overstories of Other Conifers

Where the overstory in a two-storied stand consists primarily of conifers other than ponderosa pine, the understory is likely to be somewhat poorly stocked and patchy. Understory trees larger than about 4 inches diameter are likely to be especially susceptible to blowdown if the overstory is cut in one operation.

The shelterwood method is the most appropriate for reproduction where dwarf mistletoe infection is not severe. The first cut should remove about 30 percent of the overstory basal area where the windfall hazard is average. Remove 10 to 20 percent where it seems greater than average. Two to four additional cuts at intervals of 5 yr or more should remove the rest of the overstory. Cuts should be lightest and most numerous where the windfall hazard is greatest. Between the first and last removal cuts, the understory should become windfirm, and poorly stocked places should fill in. Places that are seriously understocked at completion of the final cut should be planted promptly.

Where patches of the understory are heavily infected with dwarf mistletoe, the overstory and understory should both be removed, and the patches regenerated artificially if necessary.

Aspen Overstories

Many aspen stands have mixed conifer or spruce-fir understories. If the understory is

primarily of saplings, and conifers are to be favored, the overstory should ordinarily be removed carefully and completely in a single cut. This provides complete release, and vigorous aspen suckers will ordinarily fill the gaps.

Where much of the understory is of seedlings, it is preferable to leave about 60 ft^2 of overstory basal area to suppress the vigor of suckers that might otherwise outgrow and seriously inhibit development of the conifers. Later, when the understory has reached 8 to 12 ft in height, it will benefit by removal of the remaining overstory aspen. Suckers should fill in the stand gaps.

Where the coniferous understory includes numerous trees 4 inches or larger in diameter, the overstory should be removed in three installments over a 10- to 15-yr period, much as a ponderosa pine overstory would be removed, to avoid serious understory blowdown.

If aspen predominance is to be maintained for scenic or other reasons, the aspen should be clearcut in one operation. In that case, maximum destruction of the understory is desirable during logging, as described later in the section on logging. If conditions permit, consider letting the slash cure in place and broadcast burning during the dormant season to stimulate maximum suckering and eliminate culls and surviving conifers.

THREE-STORIED STANDS

In three-storied stands the overstory trees may be fairly windfirm except where they form large groups. The second story, on the other hand, is likely to be quite susceptible to windfall. A one-cut removal of the overstory is likely to result in serious blowdown in the second story. If the merchantable second story trees are removed in the same cut to avoid their loss by blowdown, or if they blow down and are salvaged, the patchy lower story will not approach adequate stocking. Extensive planting will then be necessary unless the area restocks adequately by aspen suckering.

Where dwarf mistletoe is not severe in the middle and lower stories, the overstory can be removed in two or three cuts over a 10- to 20-yr period. Light improvement, salvage, and sanitation cutting may also be appropriate in the lower stories at those times. The resulting stand will be essentially two-storied, and no further reproduction cuttings will ordinarily be appropriate until the new overstory is mature. One or more sanitation cuttings may be needed after a few years, when time and increased sunlight have brought out latent dwarf mistletoe infections.

In other cases, dwarf mistletoe is rather severe in the middle and lower stories. In some such stands the species mixture will permit the above-described treatment. Cutting should discriminate against the infected species. At least two subsequent sanitation treatments commonly will be needed. Parts of some stands may be sufficiently infected that patch clearcutting is desirable, or even clearcutting of the entire stand. Clearcutting should include removal or destruction of infected advance regeneration; it may sometimes be more efficient and effective to remove all regeneration of significantly infected species. If sufficient aspen were present before logging, suckering may restock much of the area. Provision should be made to regenerate promptly and effectively those parts of the area which do not sucker adequately, or where browsing threatens to eliminate the sucker stand.

MULTI-STORIED STANDS

Virgin multi-storied stands, though no longer numerous, will be considered first to establish some principles.

Virgin Stands

In examining a virgin multi-storied stand prior to preparing treatment recommendations, the silviculturist should first consider what would be left if all overmature or defective trees are removed. Commonly, the residual stand would be rather open and susceptible to severe windfall. In some cases the sapling and pole classes would not constitute effective growing stock because of heavy dwarf mistletoe infection. In patches or stands where dwarf mistletoe is serious and host specificity cannot be used to control it, the best choice may be to clearcut and plant.

If dwarf mistletoe is not serious, or if host specificity can be used to control it, then windfall will usually be the primary consideration in the first treatment. Ordinarily not more than 30 percent of the overstory basal area should be removed in the first cut. Where the blowdown hazard seems greater than normal, 10 to 20 percent may be more appropriate. That will usually mean some decadent and otherwise defective trees will be left, but taking them all would likely open the stand excessively. Up to 30 percent of the basal area of subordinate stories may be removed at the same time.

Although, strictly speaking, even the first cut s a reproduction cut, its purpose is to begin the nversion of an old, more or less decadent tand to a healthy, productive stand. Therefore, harking criteria are those of a salvage, sanitaon and improvement cut.

The rest of the overmature trees can be emoved in two or more additional cuts at 5- to 0-yr intervals.

For substantial patches strongly dominated y overmature trees, methods discussed under ingle-storied, two-storied, or possibly threetoried stands may be appropriate.

Subsequent prescriptions will depend on what he stand looks like after the overmature trees re gone, and on whether the objective is an ven-aged or an uneven-aged stand.

utover Stands

In many multi-storied stands, many or all of he overmature trees have already been removd, along with some younger trees. These stands re now likely to be fairly windfirm. Where warf mistletoe is not too serious in trees of the ole class and smaller, there are two main anagement options:

The stand can be managed under the election system, maintaining its multitoried character. Cutting should work toward a alanced age-class distribution while discriminating against trees with defects.

The stand can be adapted to even-aged anagement by restricting cutting largely to lder trees, opening the stand as necessary to stablish and release regeneration.

warf Mistletoe Infected Stands

Parts of a stand may be unmanageable ecause of severe dwarf mistletoe infection. nless there are compelling reasons not to, hose patches, or even the entire stand, should e clearcut. Care should be taken to destroy dvance regeneration of infected species. This reatment will leave the site essentially untocked. Provision should be made to plant romptly those parts of the area which do not ucker adequately with aspen, or where brows ng threatens to eliminate the sucker stand.

NDERSTOCKED STANDS

irgin Stands

Where virgin stands are understocked, a very nfavorable regeneration environment is likely to be responsible. Typically these are on steep southerly slopes. If the mature and overmature trees are short, the environment is also poorly suited to growth. Fairly tall trees, on the other hand, indicate that, once established, trees grow reasonably well.

If established trees grow reasonably well, the forest manager might consider planting to obtain full stocking. Nursery seedlings may survive well on sites not suited to establishment from seed. If the prospects for successful planting seem good, a salvage cut should probably be made first. Where ponderosa pine or white pine is to be planted, the prior removal of all merchantable trees should be considered if the soil does not present a special erosion hazard. If cutting is to be light, ponderosa pine should not be planted except in larger openings.

If the site is poor for growth or unsuited to tree planting, it may be best to leave the stand untreated, especially on readily eroded sites. In stands where the larger openings produce good forage, removing most of the trees and seeding appropriate forage species may be desirable.

Cutover Stands

Stands once well-stocked sometimes remain understocked for a long time if logging is not followed by adequate regeneration. Some such areas have developed substantial grass cover, and site preparation is normally necessary to restock them without considerable additional delay. In such cases planting is more likely to be successful than seeding. Planted seedlings are not affected by germination inhibitors left by the grass, and are better able to compete with returning grass.

SOME LOGGING CONSIDERATIONS

Methods now used to log mixed conifer forests are largely the result of the narrow logging margins dictated by yesterday's low lumber prices. Those methods are sometimes not suited to the intensive forestry needed for good wood production and for the protection of associated values — the kind of forestry made feasible, if not mandatory, by today's forest values.

The economy of long logs is often desirable, but where advance regeneration is important, a 32-ft log length should not be standard. Even large tractors often must jockey around to get a long log out of a bad lay, sometimes approaching from the side to push the log with its blade or with a tread. Valuable seedlings and

saplings are broken in the process, and even larger trees may be pushed out of the way. Cutting 16-ft logs would avoid much of this damage.

When the tops of trees are dropped into openings to spare regeneration patches, the logs often are at a poor angle for winching to skid trails. The resulting siwashing can severely damage remaining trees and destroy much regeneration. To avoid this, tops are sometimes felled into regeneration, with the hope that damage done in that way will be less than from siwashing. Another alternative commonly overlooked is to fell the tree into the opening despite the bad angle, and then reduce siwashing by cutting short logs.

An important source of damage to advance regeneration is careless skid trail construction. In most mixed conifer stands, blown-down trees are scattered around the area. The skidder, in making his tractor trail, bulldozes them out of his way, often destroying seedlings and saplings wholesale and damaging or pushing over larger trees. Where advance regeneration is important, it is desirable to pre-clear skid trails. Those segments of blowdowns lying in the skid trail can be cut out with chain saws and pushed into places where damage would be least.

In some situations efforts to spare advance regeneration are undesirable. In parts of stands, or even entire stands, seedlings and saplings may be too few or too unthrifty to be worth saving. Dwarf mistletoe may be so severe in the understory that it is desirable to deliberately destroy the entire understory and start over.

Where aspen stands are to be perpetuated, felling or otherwise eliminating all merchantable and nonmerchantable trees will commonly be desirable. Full-tree logging does the best job of eliminating the young conifers and poor-quality aspen saplings on the site (Zasada 1972, Zasada and Tappeiner 1969a, 1969b). Fellers can deliberately fell trees into young growth, and enroute to the main skid trails, skidders can deliberately drag trees, full length and with tops and branches attached, through young growth.

Trips to the landing should be restricted to main skid trails appropriately spaced, however, because aspen suckering is likely to be inferior on repeatedly or heavily disturbed soil. Trees are then topped and limbed at a topping site adjacent to the landing. The manager should be prepared to plant the topping and landing sites if he does not want to retain them as forest openings.

Skidding the merchantable bole in one piec after limbing and topping at the felling sit gives somewhat the same benefits as full-tre logging, but the area is less thoroughly disturb ed. In either case, the area should be as full cleared as economically as feasible if full vig orous aspen stocking is wanted.

Sale administration. — Poor silvicultur may result from a poor silvicultural prescrip tion, poor marking, or a contract that is weak i some important respect. It may also grow out c poor timber sale administration. As reflected i a recent task force report,[18] not every sal administrator does a good job of supervisin logging. Some resist new standards or method Some are poorly trained. A few consider the jo primarily as one of getting the logs out simpl and cheaply. A few too often accept the logger' statement as to what is reasonable or feasible either through lack of confidence or becaus they want to be liked. Even a highly qualifie and motivated sale administrator may not do satisfactory job if his time is spread over too many sales.

SLASH TREATMENT

The amount of logging slash produced i being reduced by advancing technology and increasing product demands; much materia once left on the ground as unusable is now taken out for manufacture. Also, areas once harvested are likely to contain fewer decayed logs a subsequent cuttings.

Slash has several undesirabl characteristics:

1. Wildfires are more severe and difficult to fight in areas with abundant slash.
2. Slash, particularly in large amounts, is es thetically unpleasant in many situations.
3. Some kinds of slash under some cir cumstances can cause dangerous bark beetle buildups.
4. Where a stand is clearcut or otherwise heavily opened, slash concentrations may contribute to troublesome rodent buildups.
5. Abundant slash makes planting difficult and expensive.

Disposing of slash also has undesirable characteristics:

1. It costs money.

[18] *USDA Forest Service, Southwestern Region. 1972. Timber, the resource and its harvest; an evaluation of quality in timber management. 145 p. (Unpublished task force report on file at Regional office, Albuquerque.)*

2. Where the ground would otherwise be exposed to intense sunlight, slash provides shade favorable to seedling establishment.
3. Some kinds of slash disposal can destroy much advance regeneration, and can also damage remaining larger trees.

In some situations it is best not to treat slash at all. Other situations virtually demand treatment by a specific method. On a single mixed conifer timber sale it will often be desirable to designate areas or conditions for no slash treatment, and other areas or conditions for treatment by one or a combination of methods:

1. Slash can be broadcast burned. Most of the considerations for broadcast burning were discussed in the section on fire. Broadcast burning is cheap but requires skill and care in many situations to avoid unacceptable damage. It reduces the hazards of wildfire and rodent damage. On heavily cut areas, charred trunk sections commonly provide fairly well distributed shade afterward that would have been lost if the slash had been piled before burning. Most unconsumed slash is not suitable to bark beetles. Also, it lays low on the ground and becomes inconspicuous among invading plants. Aspen suckering usually is stimulated if the area is open. On the other hand, areas with valuable seedlings and small saplings cannot usually be broadcast burned safely.
2. Slash can be machine-piled and burned. This cleans up the area as thoroughly as wanted and eliminates beetle hazard, but is much more expensive. There are several ways to machine-pile:
   a. Slash can be bulldozed into piles or windrows. This is very destructive to advance regeneration.
   b. Slash can be pulled lengthwise, branches and all, to burning sites. This greatly reduces tractor movement and the sideways movement of the slash, and reduces destruction of advance regeneration.
   c. The branches can be lopped off and the trunk pieces pulled out, reducing still further the damage to advance regeneration. This is more expensive, may make the slash harder to burn, and leaves branches on the ground; however, smaller burning sites are needed.
3. Slash can be hand-piled and burned. Damage to advance regeneration is relatively light but labor costs are high. Large, heavy trunk pieces remain, some of which may be suitable for bark beetle broods.
4. Smaller pieces can be fed into a chipper and the chips sprayed onto the ground. Effects on the chemistry and biota of the surface soil are not clear. The method is very expensive, and leaves large trunk pieces that may be suitable for bark beetle broods.
5. The branches can simply be lopped off, lowering the slash profile and reducing the wildfire hazard. Lopping is relatively cheap, although more expensive than broadcast burning. It does relatively little damage to advance regeneration and gives least benefits. Both benefits and costs are increased if branches on the underside of trunk pieces, as well as on the upper sides, are cut off, lowering the profile more and considerably speeding decay.

ARTIFICIAL REGENERATION

The discussion here in part summarizes and in part extends three previous papers (Ronco 1972, Schubert et al. 1969, Schubert et al. 1970).

In some situations, opening the canopy is all that is necessary to start a new stand. In others considerably more is needed. That "more" is the subject of this section. It includes not only planting and seeding, but site preparation, including the preparation of seedbeds for natural seedfall.

Just where artificial regeneration is needed must at present be judged entirely by the forester's ecological "feel", based largely on observation and experience. When classifications of habitat types and stand types are available, and observations and research findings have been related to them, such judgments should be easier and more satisfactory.

Site Preparation

Site preparation for planting is primarily intended to remove competing vegetation temporarily, giving the planted tree a good chance to establish itself and begin vigorous growth. Regeneration from seed requires the same help plus a suitable seedbed. In some cases the existing ground surface may be a suitable seedbed; in others a seedbed must be created if the area is to reforest from seed in an acceptable time.

Site preparation is often expensive. The same benefits are often present without expense, however, partly as a temporary holdover from the repressive effects of past shade and partly as incidental side effects of logging or slash disposal. If planting or seeding follows promptly after logging or slash disposal, the costs of

site preparation can often be avoided. Such timing requires foresight and planning. Suitable planting stock or seed must be on hand at the right time. Planting or seeding contracts must be prepared and awarded ahead of time, or a crew and equipment otherwise arranged for. Where a stand has been destroyed by wildfire, salvage logging must be prompt or the site may be lost.

If planting or seeding is delayed, or if the site is initially not suitable, then site preparation is necessary for successful regeneration. Delaying planting on a new burn, or seeding grass on it, can result in a need for site preparation on thousands of acres, at a cost of tens or even hundreds of thousands of dollars.

A supervisor may examine a site at winter's end and decide there is too little grass to require site preparation. He should keep in mind that occupation by grass always looks lighter at that season, especially if grazed the previous summer. Also, a moderate stand of grass on a dry site may compete as seriously as heavy grass on a moist site.

Complete site preparation. — Complete site preparation removes all or nearly all the competing vegetation. It is needed mainly on "lost" sites, where grass or shrubs have taken over after past fires or cutting. Complete site preparation provides the best survival and juvenile growth. If done mechanically it is very expensive, especially in the Gambel oak scrub type. Ordinarily, if the expense of complete mechanical site preparation is needed, it should be followed by planting instead of the more uncertain seeding.

Complete site preparation with herbicides can be very effective. If the chemicals and procedures used avoid environmental damage, it is also much less costly than using heavy equipment. While these are sites already lost, and haste is seldom needed, foresight and planning remain important. Preparation and approval of the necessary environmental impact statements take time. Also, vegetation ordinarily must be chemically treated the summer before planting.

Dalapon with, or followed by, atrazine can give good control of herbaceous vegetation. Dalapon will kill existing grass and some forbs. Atrazine prevents quick establishment of new competition from seed; it is suitable only for sites to be planted, not sites to be seeded.

Response to dalapon may vary somewhat between species and sites. In general, however, 5 lb active ingredient per acre should be applied the summer before planting. Much heavier dosages may give inferior kill of grass roots although the forb kill may be higher. The plants must be green and growing at the time of treatment; when they are setting seed may be too late. The spray must be recently mixed; it deteriorates in storage.

Five lb active ingredient per acre is also about right for atrazine. It too should be applied the summer before planting.

Oak brush can be controlled by aerial spraying with a mixture of 2,4,5-TP and tordon (Marquiss 1973), but the dead stand remains a serious impediment to planting.

Complete site preparation does not, of course, rule out leaving patches of meadow or oak brush within the area to provide diversity of scenery and wildlife habitat.

Partial site preparation. — Scalping with mattocks has been a common means of site preparation. For more than a small, extremely temporary effect, the scalp should be at least 18 by 18 inches. The soil beneath smaller scalps is too quickly reoccupied by grass roots. Larger scalps are safer. Scalping with hand tools can be effective if done properly, but good hand scalping is expensive because of the labor and supervision required. To be useful, scalping must grub out the root crowns of the grass and weeds. Such labor is slow, strenuous, and unpopular. Not infrequently what is actually done is hand **scraping,** which is much faster and cheaper but essentially worthless. The dead tops of the vegetation are scraped off the ground surface, leaving what looks, superficially, like a scalp. The worker may really think he has done a good job, but a close look reveals the root crowns still in place. New tops will grow as soon as the weather is favorable. Money, labor, and usually a seedling have been wasted, and the spot remains unstocked.

A conscientious but poorly trained planter may plant in a small patch of bare ground between grass clumps, where no scalp seems needed. All too often the surface is bare but the soil beneath it is occupied by grass roots from adjacent clumps, and what seems to be planting amounts to premature burial.

In training and supervising scalpers, therefore, emphasis must be put on:

1. Making large enough scalps,
2. Leaving no root crowns,
3. Not planting in bare ground occupied by roots of adjacent grass clumps.

The scalper selects the place where the seeding will be planted. Additional training and supervision are therefore important to assure the selection of suitable microsites, especially for species such as Engelmann spruce that are initially intolerant of full sunlight.

Partial site preparation can also be done with powered hand tools and by tractor equipment. Light bulldozers have been used to scalp patches or continuous strips. A strip scalper with a subsoiler suitable for rough stony ground is being developed. The initial model was designed by George Cullum of the Sitgreaves National Forest. It puts topsoil into the subsoil slip, and helps tree roots penetrate more rapidly below the zone of intense root competition from reinvading grass. An ordinary plow furrow is not an adequate strip scalp.

Strips bulldozed in brushfields have been tried in almost every region of the country where there are brushfields to rehabilitate. California has been a notable example (Schubert and Adams 1971). In general, results have been unsatisfactory, mainly due to brush encroachment and animal damage. Deer, elk, and cattle tend to use the strips as main travel routes, and seedlings are browsed or trampled.

Water-repellent soils. — Wildfires cause major reforestation needs. Because suitable planting stock is seldom available to reforest large burns before serious vegetative competition develops, managers must often resort to seeding. Prompt aerial seeding of such areas has sometimes been very successful in the Southwest. Where fire has made the soil water-repellent, however, failure can be expected unless salvage logging or other disturbance has broken up the thin repellent layer. Parts of burns undisturbed by salvage logging should be examined, and where significant areas are water repellent, seedbed preparation should precede broadcast seeding (DeBano and Rice 1973).

Sometimes undisturbed forest floors also have a thin water-repellent layer, just below the litter layer. This layer may account for some regeneration failures. Strong water repellency can occasionally be found even in severely disturbed soil in skid trails, but apparently it is spotty. We need to know more about the extent of water repellency in the absence of fire and what to do about it.

Site preparation in partially cut stands. — So far we have considered site preparation on largely deforested land. Where advance regeneration is inadequate, seedbed preparation may also be desirable within the shelterwood and selection systems. Logging disturbance and slash disposal sometimes provide too few good seedbeds. Seeding skid trails and other disturbed ground with grass has sometimes seriously delayed regeneration.

A thick organic surface layer often inhibits seedling establishment. Prescribed burning may prove a valuable method of improving such seedbeds following the seed cut in the shelterwood system. The burn would have to reduce the thickness of litter and humus layers appreciably without significantly damaging the shelterwood itself. Such light fires will probably seldom make the soil water-repellent.

Prescribed fire seems to hold less promise for site preparation in the selection system because the areas to be treated would be very small, scattered, and interspersed with areas of sensitive seedlings and saplings. In the selection system, seedbed needs should be considered when prescribing methods of logging and slash disposal.

It should be much easier to diagnose and prescribe for seedbed needs when habitat type and stand type classifications become available.

Seeding

Research in artificially seeding Southwestern conifers has been exploratory.

Without human intercession, nature often takes many years of seeding and reseeding to regenerate an area. In artificial seeding we want to restock the area with a single sowing. This means providing conditions favorable to germination, survival, and early growth.

In Southwestern mixed conifer forests the two most important factors limiting the success of seeding seem to be rodents and frost heaving. In some situations, success is limited or prevented by soil drying or by organic decomposition products that inhibit germination and growth. On southerly slopes it is likely that heat girdling sometimes causes critical losses.

In selecting the species to be sown, rate of root penetration, especially first-year penetration, is a primary consideration. Deep-rooting species are less susceptible to frost heaving and soil drying.

Spot seeding cannot be recommended unless the spots can be protected from rodents. In the absence of rodent control, broadcast seeding may succeed, however, if enough seed is sown to feed the mice and still provide a seedling stand.

On fairly large areas, experience suggests that 100,000 to 200,000 seeds per acre are enough, particularly if substantial natural seedfall in the surrounding area prevents or reduces the movement of additional mice into the seeded area. On small areas, rodents may concentrate so heavily that 200,000 seeds per acre are not enough, even on a good seedbed. If the seed germinates promptly after sowing, rodents have less opportunity to eat it, although they can eat a lot of seed in a single night. Therefore, seeding commonly is best done when the first summer rain storm has been forecast. This has been called "seeding under a cloud."

The seed must be suited to the site. Species suitability has been touched on and will be considered further in the section on planting. Within a species, seed origin has repeatedly been proved important. Schubert and Pitcher's seed zones (1973) provide a basis for selecting seed sources. In addition, the source elevation should not differ by more than 500 ft from that of the area sown. Within a zone and elevation, habitat type too is probably of some importance (Silen 1964).

Planting

Reliable procedures for handling and planting coniferous seedlings have been demonstrated in the Intermountain Region and on the National Forests of Arizona, Colorado, and New Mexico. Because they have been covered in planting schools on most National Forests in the Southwest and are largely described by Ronco (1972) and Schubert et al. (1970), they will not be reviewed here except to comment on auger planting.

The advantages of auger planting have become increasingly appreciated in the Southwest during the last year or two. With a auger, it is much easier to make a hole dee enough for long-rooted planting stock, an correct planting is easier. Acceptance of auger has been slowed, however, by the common belie that augers cannot be used in stony soils Actually, experience has demonstrated that fe areas are too stony for auger planting (fig. 16 Augers can be used in ground too stony to di adequate holes with a mattock. Only on th most extreme stony sites must one resort to planting bar.

The primary consideration dealt with in th rest of this section is matching the species to th planting site. On mixed conifer forest land selection of the species to plant can make a important difference in plantation survival an growth.

Because neither white fir nor corkbark fir ha been tested as a plantation species in th Southwest, no large-scale planting of them ca be recommended at this time. Small-scale trial are desirable to evaluate problems and poten tials.

Where heavy use of an area by deer, elk or cattle is expected, many planted pon derosa pines or Douglas-firs may be killed, an the less palatable Engelmann spruce, blu spruce, and white pine should be considered Sheep sometimes browse them heavily too Chemical repellents are available for treatin planted trees, but their success has been erratic

Where serious trampling or browsing b livestock would be expected, consider keepin livestock out of the plantation for several years.

On sites where planted trees will b shaded, as where numerous aspen overstor trees remain, shade-tolerant species should b used. This choice is even more important wher abundant aspen suckering is expected Engelmann spruce is definitely more shade tolerant than Douglas-fir or blue spruce Therefore Engelmann spruce should be serious ly considered for shaded northerly slopes abov about 8,500 ft and for southerly slopes above about 9,000 ft. On warmer sites, Douglas-fir o blue spruce should be favored.

In general, Douglas-fir seems suited to moderate shade both on southerly slopes between 8,000 and 10,000 ft and northerly slopes between 7,500 and 9,500 ft.

On sites exposed to full sunlight, ponderosa pine seems generally the most satisfactory species for planting below 9,500 ft on southerly slopes and below 9,000 ft on northerly slopes, unless there is a prospect of serious browsing damage. White pine seems well suited to the same sites and is not very attractive to game or cattle. Its tendencies to

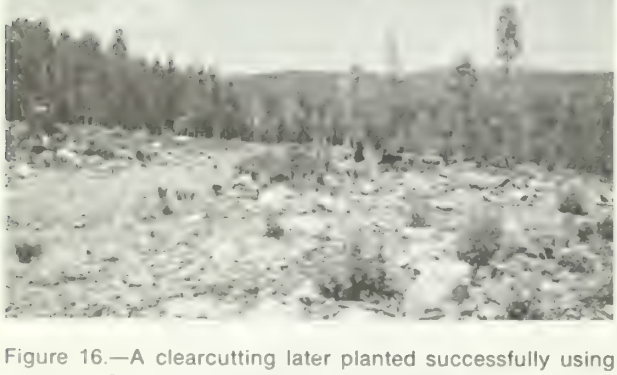

Figure 16.—A clearcutting later planted successfully using augers. Occasional patches were skipped by the auger men and planted with bars. Apache National Forest.

ow coarse branches and crooked stems, wever, make it less desirable than other ecies for timber. White pine should be planted a spacing no greater than 6 by 6 ft to improve m and reduce branch size. White pine seed ould be from the best-formed trees available.

There is no native species whose suitability s been adequately demonstrated for planting fully exposed situations above 9,500 ft in the uthwest. Where exposed high-elevation sites uire planting, Engelmann spruce can be ccessfully established, however, if seedlings e carefully planted in the shade of logs, mps, and so forth (Ronco 1972). Trees nted a foot away from a log on its north side e too far from the log to get any shade in ring and summer. They must be planted as se to the log as possible. This also reduces mpling damage. Where dead shade is not ailable, an upright shingle or similar object y be firmly planted in or very close to the nting hole on the south side of the seedling nco 1967). If planted firmly, the shingles are t likely to be pushed over onto the seedlings snow, except perhaps on those steep slopes ere shade would have to be provided from the ill side of the seedlings.

Aspen and lodgepole pine are possible future ernatives to Engelmann spruce for planting open high-elevation sites. The nursery oduction of aspen planting stock from seed s been described (Benson and Einspahr 1962, nspahr 1959), as have techniques for growing en directly or indirectly from root cuttings nson and Schwalbach 1970, Farmer 1963, rr 1971, Zufa 1971). Genetic differences ween aspen clones may provide real opportities for the selection of genotypes with perior autumn coloration, growth, or disease istance characteristics (Egeberg 1963, aham et al. 1963, Rudolf and Patton 1966, ll 1971).

Lodgepole pine seedlings survive much better full sunlight than do Engelmann spruce nco 1967). Lodgepole pine is not native to the uthwest, but was introduced in 1911 on the umbine Ranger District of the San Juan tional Forest, where its development has n quite satisfactory for 60 years. The species s subsequently been planted extensively on h San Juan National Forest. Survival has n generally good, even at elevations that em high for lodgepole pine, but juvenile wth is said to have been disappointing in ne cases. It has not been tested farther south he region, but probably would prove suitable conservative elevations — between about 00 and 10,500 ft.

Both aspen and lodgepole pine modify the harsh radiation environments of exposed high-elevation sites, making them much more suitable for invasion by the native climax occupants, Engelmann spruce and corkbark fir.

Intermediate Treatments

Intermediate treatments, such as thinning, are not intended to replace an old stand with a new one, or old trees in a selection forest with seedlings, although they may result incidentally in reproduction. Rather, they are made to maintain or improve the growth and condition of existing stands.

No research has been done on intermediate treatments for Southwestern mixed conifer forests. The following discussions and tentative recommendations are based on ecological behavior and general observations, and on research done in other regions.

THINNING

Thinnings are made to give the remaining trees more resources for growth.

Conifers

In mixed conifer forests, overstocking does not often seem to interfere with normal height growth. Only occasionally are young stands or patches seen in which poor height growth appears to result from extreme overstocking (Jones 1971).

On the other hand, diameter growth in many sapling and pole thickets could be improved by thinning. No work has been done toward recommending optimum stocking levels. A relatively inexpensive thinning practice — "crop tree" thinning — does not require stocking level recommendations, however. A form of crown thinning, it favors only trees with good potential as high-quality crop trees. The criteria for selecting trees to favor include more than current quality: trees selected should also seem likely to remain free of dwarf mistletoe, and they should have one or more crown competitors whose removal would help their development substantially. It is best to mark the competitors to be removed. An alternative is to mark the trees to be favored; the cutters are then given a rule of thumb for deciding what competitors to cut. One such rule used in other regions has been to remove all crown competitors growing within a distance, in feet, equal to the crop tree d.b.h. in inches, plus 4. Thus a 6-inch-

diameter crop tree would be left with no crown competitors growing within 10 ft.

Aspen

In aspen thinning experiments in the Lake States and Canada, diameter growth was accelerated on most trees, although the larger trees on unthinned plots grew about as well as those on thinned plots. The primary benefits were shortened rotations or an increase in the average size of material produced in a given rotation (Anderson and Anderson 1968, Sorensen 1968, Steneker and Jarvis 1966, Zehngraff 1947). An economic evaluation by Noreen[19] suggests, however, that even with multiproduct markets, precommercial thinning is uneconomical for aspen timber production. Thinnings delayed until profitable material can be removed may not shorten the rotation or provide larger material (Hubbard 1972, Schlaegel and Ringold 1971), although the operation may salvage material that would otherwise die and be lost (Hubbard 1972, Schlaegel 1972).

Hypoxylon canker has been reported as more severe on thinned plots than on unthinned, despite discrimination against infected trees during thinning. It was also speculated that the larger branch stubs in thinned stands might eventually result in more trunk rot (Anderson and Anderson 1968).

On the San Juan National Forest it has been observed that cattle make little use of the abundant herbaceous forage in dense aspen sapling stands. Apparently they find it difficult to move around in them. It may sometimes be worthwhile to thin aspen sapling stands for the combined benefits of better cattle grazing and shorter rotations. Several studies (Sorensen 1968, Steneker and Jarvis 1966, Zehngraff 1947) suggest that sapling spacings of approximately 8 by 8 or 10 by 10 ft are appropriate.

SALVAGE CUTTINGS

Salvage cuttings are solely or primarily for salvaging dead, diseased, insect-damaged, or blown-down trees. Salvage is also accomplished during thinnings and improvement and reproduction cuttings, if merchantable trees are removed which would be lost before the stand is next treated.

[19]*Noreen, P. A. 1968. Economic evaluation of precommercial thinning in good-site aspen. M. S. report, Coll. For., Univ. Minn. 19 p. (Cited by Hughes and Brodie 1972).*

When a stand is being examined for possib salvage cutting, the forester should ask if th value of salvageable material is worth the cos of logging, protection of regeneration, ar possible slash treatment connected with th operation.

In preparing a salvage cut, considerations discussed under reproduction methods oft apply. Marking a stand heavily for full salva may well open it to the extent that seve windfall will result.

SANITATION

Sanitation is the treatment of diseased insect-infested trees that menace the health nearby trees. It is often part of reproduction salvage cutting, but it may also be a separa operation. Individual infected trees may b removed to avoid the spread of dwarf mistleto for example, or a stand may be clearcut where serious insect epidemic threatens to spread other stands. Since such clearcutting is likely necessitate an expensive reforestation job, an may have important esthetic and recreation impacts, it should not be decided upon lightly

CLEANING AND IMPROVEMENT CUTTINGS

Cleaning is the removal of saplings of inferi form or less desirable species that are competin with better saplings. Thinnings in saplin stands often constitute cleanings as well.

Cleanings can also have a sanitation aspec For example, cleaning should remove sapling with visible dwarf mistletoe infectio Cleanings may also remove saplings that hav been exposed to dwarf mistletoe infection, eve though they show no signs of infection, if the compete with good saplings of uninfecte species.

Improvement cuttings have the same gener purpose as cleanings, but are made in stands stories beyond the sapling stage and ofte remove merchantable material. As in cleanin trees of inferior form or condition or of speci less desirable in the stand are removed if the compete with better trees.

In managed stands on the rotations of th future, and in a world of increasing consume pressures, there are unlikely to be any low-val species. But on a given site one or more speci may have inferior growth potential or be le desirable for other reasons.

WHAT WE NEED TO KNOW

Ecosystem classification deserves the highest esearch priority, as much research observaon, and experience, becomes considerably ore meaningful and useful when related to abitat and stand types.

Growth prediction tools are also needed. hese include tables or equations for predicting ields of mixed and uneven-aged stands as well s for pure even-aged stands. It is likely that ost mixed conifer land in the region will ontinue to be occupied by mixed stands egenerated under a forest canopy. Classificaon of habitat and stand types should provide a seful foundation for development of yield redictors.

Most research on the silvics and silviculture f Southwestern mixed conifers has been riented toward regenerating clearcuttings and ther deforested land. While we do not yet know ll we need to about that important subject, oday we need to give much more attention to he potentials and problems of the shelterwood nd selection systems.

In addition, serious work is needed on conomic and ecological models as aids in ultiple use planning and decisionmaking. As pinoffs, modeling also helps define key esearch needs that might otherwise go too long nrecognized, and points up relationships that nay otherwise be overlooked.

Aspen occupies more than 6 million acres in he interior West. We need to know much more bout its ecology and management.

Those are general areas. The following is a artial list of more specific problems. We need to now more about:

1. Recognizing good growing stock in understories.
2. Response of understories to different degrees of release.
3. Spread and intensification of dwarf mistletoe in different habitat and stand types.
4. Evaluation of forest floors as seedbeds in shelterwood and selection forests.
5. Potentials and considerations in prescribed burning.
6. Water repellency in burned-over and unburned soils.
7. Factors affecting survival and growth of seedlings in shelterwood and selection forests.
8. Prescriptions for intermediate treatments.
9. Development of nursery and planting practices for aspen.
10. Tests of exotic conifers for reforesting exposed high-elevation sites.

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COMMON AND SCIENTIFIC NAMES OF PLANTS, VERTEBRATES, INSECTS, AND DISEASES MENTIONED

Nonparasitic Plants

Aspen (quaking)	*Populus tremuloides* Michx.
Bracken	*Pteridium aquilinum* (L.) Kuhn
Douglas-fir (Rocky Mountain)	*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco
Fescue, Arizona	*Festuca arizonica* Vasey
Fir, corkbark	*Abies lasiocarpa* var. *arizonica* (Merriam) Lemm.
Fir, subalpine	*A. lasiocarpa* var. *lasiocarpa* (Hook.) Nutt.
Fir, true	*A.* spp.
Fir, white	*A. concolor* (Gord. & Glend.) Lindl.
Juniper	*Juniperus* spp.
Oak, Gambel	*Quercus gambellii* Nutt.
Orchardgrass	*Dactylis glomerata* L.
Pine, Apache	*Pinus engelmannii* Carr.
Pine, Arizona	*P. ponderosa* var. *arizonica* (Engelm.) Shaw
Pine, bristlecone	*P. aristata* Engelm.
Pine, Chihuahua	*P. leiophylla* var. *chihuahuana* (Engelm.) Shaw
Pine, ponderosa	*P. ponderosa* Laws.
Pine, southwestern white	*P. strobiformis* Engelm.
Pinyon	*P. edulis* Engelm.
Raspberry	*Rubus* spp.
Spruce, blue	*Picea pungens* Engelm.
Spruce, Engelmann	*P. engelmannii* Parry

Vertebrates

Deer (Coues)	*Odocoileus virginianus couesi* (Coues & Yarrow)
Deer (mule)	*O. hemionus hemionus* (Rafinesque)
Deer mouse	*Peromyscus maniculatus* (Wagner)
Elk	*Cervus canadensis nelsoni* Bailey
Ground squirrel	*Citellus lateralis* (Say)
Ground squirrel	*Eutamias spp.*
Hare	*Lepus americanus* (Erxleben)
Junco	*Junco* spp.
Meadow vole	*Microtus* spp.
Pocket gopher	*Thomomys* spp.
Porcupine	*Erethizon dorsatum* Linnaeus
Rabbit	*Sylvilagus* spp.
Shrews	*Sorex* spp.
Squirrel (red)	*Tamiasciurus hudsonicus* (Erxleben)

Diseases

Cenangium canker	*Cenangium singulare* Davidson & Cash
Ceratocystis canker	*Ceratocystis* spp.
Dwarf mistletoe	*Arceuthobium* spp.
Dwarf mistletoe, Apache	*A. apachecum* Hawksworth & Wiens
Dwarf mistletoe, Douglas-fir	*A. douglasii* Engelm.
Dwarf mistletoe, (no common name)	*A. blumeri* A. Nelson
Dwarf mistletoe, southwestern	*A. vaginatum* subsp. *cryptopodum* (Engelm.) Hawksworth & Wiens
Dwarf mistletoe, western spruce	*A. microcarpum* (Engelm.) Hawksworth & Wiens
Dwarf mistletoe, white fir	*A. abietinum* Engelm. ex Munz f. sp. *concoloris* Hawksworth & Wiens
Hypoxylon canker	*Hypoxylon mammatum* (Wahl.) Mill.
(no common name)	*Bacillus thuringiensis* Berliner
(no common name)	*Wallrothiella arceuthobii* (Pk.) Sacc.
Spruce broom rust	*Peridermium coloradense* (Diet.) Arth. & Kern
White trunk rot	*Phellinus tremulae* (Bond.) Bond. et Boris (=*Fomes igniarius* var. *populinus)*

Insects

Arizona five-spined engraver	*Ips lecontei* Swaine
Douglas-fir beetle	*Dendroctonus pseudotsugae* (Hopkins)
Douglas-fir tussock moth	*Hemerocampa pseudotsugata* McDunnough
Fir engraver	*Scolytus ventralis* Leconte
Mountain pine beetle	*Dendroctonus ponderosae* Hopkins
New Mexico fir looper	*Galenara consimilis* (Heinrich)
Roundheaded pine beetle	*Dendroctonus adjunctus* Blandford
Southwestern pine tip moth	*Rhyacionia neomexicana* (Dyar)
Spruce beetle	*Dendroctonus rufipennis* (Kirby)
Western budworm	*Choristoneura occidentalis* Freeman
Western tent caterpillar	*Malacosoma californicum* (Packard)
White fir needle miner	*Epinotia meritana* Heinrich

U.S. GOVERNMENT PRINTING OFFICE: 1974---781-700

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1974. Silviculture of southwestern mixed conifers and aspen: the status of our knowledge. USDA For. Serv. Res. Pap. RM-122,44p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521

Describes the status of our knowledge about mixed conifer silviculture in the interior Southwest. Ecological background is reviewed first, followed by description of silvicultural methods. Relevant literature is discussed, along with observations, experience, and results of unpublished research. Contains unpublished input by subject-matter specialists and southwestern forest managers, largely as feedback from their reviews of a working draft. Research needs are also considered. Aspen forests are included; in the Southwest they are usually succeeded by mixed conifers.

Oxford: 614. **Keywords:** Silviculture, forest regeneration, *Abies concolor, A. lasiocarpa* var. *arizonica; Picea engelmannii, P. pungens; Pinus ponderosa, P. strobiformis, Populus tremuloides; Pseudotsuga menziesii* var. *glauca.*

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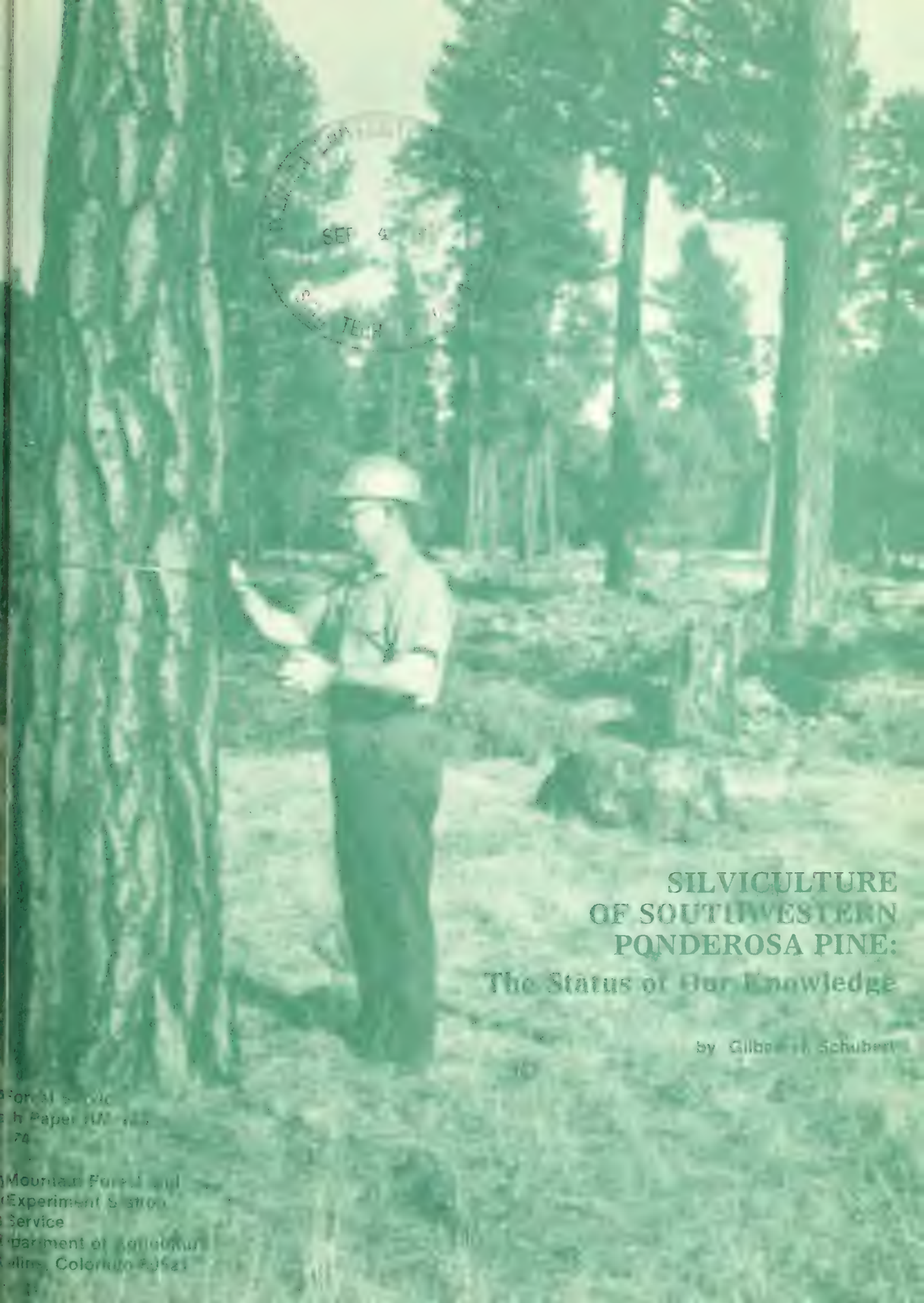

SILVICULTURE OF SOUTHWESTERN PONDEROSA PINE:
The Status of Our Knowledge

by Gilbert H. Schubert

Forest Service
Research Paper RM-123
1974

Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado 80521

Abstract

Describes the status of our knowledge of ponderosa pine silviculture in the southwestern States of Arizona, Colorado, New Mexico, and Utah. Economic value, impact on other uses, and the timber resource are discussed first, followed by ecological background, site quality, growth and yield, and silviculture and management. Relevant literature is discussed along with observations, experience, and results of unpublished research. Treatise is intended to serve as a reference tool for guidance in making management decisions and prescribing silvicultural treatments. Research needs are also considered.

Oxford: 911:174.7:181:174:815:614. **Keywords:** *Pinus ponderosa*, timber resource, silvicultural treatments.

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USDA Forest Service
Research Paper RM-123

June 1974

SILVICULTURE OF SOUTHWESTERN PONDEROSA PINE: The Status of Our Knowledge

Gilbert H. Schubert, Principal Silviculturist
Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained at Fort Collins. in cooperation with Colorado State University; research reported here was conducted at Flagstaff, in cooperation with Northern Arizona University.*

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

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SILVICULTURE OF SOUTHWESTERN PONDEROSA PINE:

The Status of Our Knowledge

Gilbert H. Schubert

INTRODUCTION

Ponderosa pine[2] forests have featured in
e development of the Southwest since the
old Rush days of the mid 1800's. These lands
ve not only supplied a wide variety of timber
oducts, but also have produced abundant for-
ge and long have been grazed by livestock.
ese forests produce much of the region's
er, elk, antelope, turkeys, and other wildlife.

Other uses of these lands are becoming in-
easingly important. Recreational use has
en expanding at a rapid rate. A major portion
the usable water is produced in this timber
pe. Hunting has always been an important use
d is expected to increase. Each year, more
ople are enjoying the esthetics and becoming
ore concerned about the use of these forests.
mber management activities have an impact
virtually all these uses of the forests. Forage
oduction and habitat for big-game animals
ay be benefited by opening up timber stands.
ater yields are influenced by stand manipula-
ons. Recreational and esthetic values may be
proved following the short period required
r development of ground vegetation. Current
proaches to forest management are being in-
easingly oriented to enhancing these aspects
multiple use.

Forest managers in the Southwest have
ticeably shifted their emphasis to more in-
nsive practices, particularly on the more pro-
uctive lands and lands with special qualities.
anagers are now faced, however, with an in-
easing demand to improve their forestry practices, particularly on Federal and State lands. These demands stem from a need for more timber and other forest-related resources, and a need to produce these goods and services without irreparable environmental damage or visual degradation. To make sound management decisions, foresters must be able to find and use the considerable pool of knowledge on the ecology, silviculture, and management of southwestern ponderosa pine forests accumulated through research during the past 60 years.

This publication summarizes technical information and observation that is now available in many separate reports, including some hitherto unpublished data. Therefore, the primary emphasis in this report will be to bring together the more important facts to serve as a reference tool to the forest manager. The coverage is admittedly timber oriented. The manager may require more detailed information. Literature citations will help direct him to specific publications. This report will also serve to identify areas in which information is fragmentary or entirely lacking. Scientists should find this useful in development of research programs and specific studies.

[2]*Common and scientific names of plants, animals, diseases, and insects commonly associated with southwestern ponderosa pine type are listed in the appendix.*

HISTORICAL REVIEW

Past Activities

The first harvest cutting in the southwestern ponderosa pine forests occurred in the Front Range of the Southern Rocky Mountains in Colorado about 1860 (Clapp 1912, Pearson 1910, Pearson and Marsh 1935). During the Gold Rush years, tens of thousands of acres were virtually clearcut for fuel, mine timbers, and

lumber. Elsewhere in the Southern Rockies, areas that escaped the early clearcuttings were selectively cut. Many of the clearcut areas are now occupied by second-growth, and the sites are often understocked or unstocked as a result of destructive fires. Selectively cut areas are in better condition.

Cutting in Arizona and New Mexico became commercially important with the construction of the transcontinental railroad in the 1870's and 1880's. The big demand was for bridge timbers and railroad ties, although considerable amounts of timber were also cut for mine props, lumber, and land clearing. By 1890, a flourishing lumber business had been established.

Many of the early cuts in Arizona and New Mexico were heavy (Pearson 1910, Pearson and Marsh 1935). Cuts during the railroad logging days generally removed 70 to 80 percent of the merchantable volume. Some areas were laid waste, and huge amounts of slash accumulated which lead to some disastrous fires.

With the advent of truck logging in the 1930's, the cuts throughout the Southwest became lighter. However, some cuts were still made to a minimum 10- to 12-inch diameter limit on both private and railroad grant lands. Cuts on Federal lands averaged about 50 percent of the volume, primarily removing mature and decadent trees. Earlier recommendations were followed which suggested that cuts in virgin stands not exceed two-thirds of the merchantable volume, and in some areas should be considerably less than 50 percent (Clapp 1912). The objective during this period was to select the old decadent groups near areas with advance reproduction first.

On many of the Federal forests, selective cuttings were made in a series of light cuts which generally amounted to the shelterwood method (Clapp 1912, Pearson 1910). These light cuts eventually removed 60 to 70 percent of the volume, and then a removal cut was made 10 to 20 years later after reproduction was established. Specific references were made to these series of light preparatory cuts under the shelterwood method on the Prescott National Forest. Similar cutting treatments were probably applied on other Federal and private lands as well. The reproduction following these cuts was frequently rated as good to excellent.

Many earlier foresters recognized the importance of groupwise stand structure and the need to modify their cuttings accordingly. Many stands had very little advance reproduction, and numerous references were made to the open parklike appearance (Pearson 1950). In certain areas, foresters recognized a need for constraint on cutting unless reproduction was already established.

One of the needs recognized early in the history of man's manipulation of the forest was for sanitation-salvage cuttings. Heavy natural mortality was common due to the high proportion of overmature stands. Mortality has been considerably reduced in these partially cut stands (Myers and Martin 1963a, 1963b; Pearson 1950). Lightning, wind, dwarf mistletoe, and insects have been the main causes of mortality, with oldest and least vigorous trees being most susceptible.

In the early 1940's, sanitation-salvage gave way to improvement selection (Pearson 1942). The improvement selection method has the additional objectives of improving the quality and reducing the density of the growing stock.

Grazing has also had an impact. Livestock was first introduced into the ponderosa pine forests in the mid 1500's by Coronado (Stoddart and Smith 1943), but serious forest range deterioration did not occur until the late 1880's (Dutton 1953). Foresters have frequently expressed concern over the injury to pine seedlings caused by the browsing of cattle and sheep, but the damage often is only of consequence where the area is overgrazed (Arnold 1950). Overgrazing was severe primarily in the 1880's and during the war years of 1916-18.

The nature of the forest has changed considerably over the years. Perhaps the greatest change occurred during the early 1900's. The change from open forests to dense stands of young growth resulted from improved logging practices, protection from fire, reduction in livestock grazing, and a 30-year wet climatic cycle which started about 1905.

Lessons Learned

Many of the earlier "facts" learned were based mainly on observations. Information passed on to succeeding foresters by men with a strong ecological background has stood the test of time. Research on a formal basis had its start at Fort Valley, Arizona, in 1908 with the establishment of the first forest experiment station in the United States (Pinchot 1947). A few of the early findings are reported here.

Ponderosa pine is not a "fire-type" (Clapp 1912; Pearson 1910, 1923, 1950; Woolsey 1911). Although old, mature, thick-barked trees are highly resistant to light ground fires, old trees are killed or severely damaged by severe crown fires. Seedlings and small saplings are killed by light ground fires. Fire is not required for seedbed preparation, but may be beneficial to reduce a heavy litter layer which would hamper seed germination. Severe crown fires within the ponderosa pine type would convert the pine forests to a grass or brush type.

Large clearcuts and burns, where all reproduction and seed trees were killed, were converted to grass or brush (Pearson 1910). During the early railroad logging days, large clearcuts covered several townships south and west of Flagstaff, Arizona. All failed to regenerate. Areas which were cut by the strip clearcut method, where strip widths ranged from one to three tree heights, frequently have excellent stands of vigorous second growth. Large clearcuts, where advance reproduction was not destroyed, are frequently fully stocked with young trees. These cuts were actually overstory removals and not true clearcuts. Overstory removal was successful only when the cut was made while the advance reproduction was under sapling size.

Some clearcuts made during a good seed year have regenerated satisfactorily (Pearson 1910, 1923; Woolsey 1911). The trees should be cut during the period between seed maturity in the fall and seed germination in the summer. The area must be cleared of competing herbaceous vegetation prior to the July after seedfall.

Excellent reproduction was obtained with the seed tree, shelterwood, and group selection methods during heavy seed years, whereas practically none occurred when areas were cut during a nonseed year (Pearson 1950). On the Coulter Ranch Plots south of Flagstaff, natural restocking was directly related to amount of shelter and seed. These plots were cut during the heavy seed year of 1913.

High rodent populations were found to be a major obstacle to establishment of natural regeneration (Pearson 1923, 1950). The adverse impact of rodents was least on areas cut during a good seed year, and thoroughly disturbed during logging.

Heavy grazing just prior to a harvest cut made during a good seed year has increased survival in some areas (Arnold 1950, Pearson 1923). Severe grazing was found to be a partial, but not a complete, substitute for mechanical site preparation. Areas grazed after cutting and before seedlings were well established are now understocked or poorly stocked.

Where advanced reproduction was present in adequate amounts, lopping and scattering of the slash was found to be beneficial (Pearson 1950). The slash, where not too dense, protected seedlings from excessive browsing by livestock, deer, and elk.

THE TIMBER RESOURCE

The basic information needed for the timber management plans and for coordination of all other resources is obtained from resource inventories. These inventories may be either extensive or intensive. The USDA Forest Service makes extensive inventories at 10-year intervals on a nationwide basis. The intensive inventories or compartment examinations are made at shorter intervals on a Forest-District basis.

The limited data collected in previous extensive inventories were lumped together for the entire Forest. These summary data were statistically sound for the Forest as a whole, but seldom depicted true on-the-ground conditions in any one specific location. The sampling intensity was too light and too few kinds of data were collected at each sample point to provide reliable information for local use. Recent procedural changes and intensification of data collection have improved the usefulness of extensive inventories in the Southwest.

Commercial Areas and Volumes

Stands more or less dominated by ponderosa pine occupy nearly 11 million acres of the 26.5 million acres of commercial forest land of Arizona, Colorado, New Mexico, and Utah (table 1). New Mexico has the largest acreage in ponderosa pine, and Utah the least.

Although much of the forest indicated as ponderosa pine cover type is essentially pure ponderosa pine, part of it may be more accurately described as mixed conifer. For example, some of the area on the Mogollon Plateau in central Arizona and the Kaibab Plateau in northern Arizona, which is classified as ponderosa pine type, has stands composed of ponderosa pine, southwestern white pine, Douglas-fir, white fir, spruces, and juniper.

Most of the area in the four States is in the sawtimber size class (table 1). Arizona and New Mexico have the greatest area in sawtimber, with nearly equal amounts in each State.

Over 500,000 acres are nonstocked. The greatest unstocked areas occur in Colorado with over 12 percent of the commercial forest land in the category.

This imbalance in stand size-class distribution poses a challenge to forest managers. Under proper management, a near balance in size-class distribution could be accomplished in about three 20-year cutting periods. It will also take a greatly expanded reforestation program to regenerate the unstocked lands and obtain prompt regeneration on areas receiving a final harvest cut.

Ponderosa pine growing stock and sawtimber are highest in Arizona (table 2). Arizona has 50 percent of the growing stock and 51 per-

Table 1.--Area of commercial forest land in ponderosa pine type by stand-size classes, 1962

State	Stand-size class					Total commercial forest land	Total in ponderosa pine
	Saw-timber	Pole-timber	Saplings and seedlings	Non-stocked	All stands		
	M acres						*Percent*
Arizona (Spencer 1966)	3,468	89	37	64	3,658	3,977	92
Colorado (Miller and Choate 1964)	1,504	553	5	285	2,347	12,275	19
New Mexico (Choate 1966)	3,885	154	101	194	4,334	6,269	69
Utah (Choate 1965)	403	14	8	7	432	3,999	11
Total, four-State area	9,260	810	151	550	10,771	26,520	41

cent of the sawtimber volume. About 86 percent of the southwestern ponderosa pine timber volume is in Arizona and New Mexico.

Stocking is also highest in Arizona, intermediate in New Mexico, and lowest in Colorado. Average growing stock volume is 1,423 ft^3 per acre and average sawtimber volume is 6,256 fbm (bd ft) per acre in Arizona. New Mexico ponderosa pine forests average 885 ft^3 per acre while sawtimber volumes average 3,735 fbm per acre. The average growing stock volume is 433 ft^3 per acre and sawtimber runs at 1,816 fbm for Colorado.

Table 2.--Volume of ponderosa pine growing stock and sawtimber on commercial forest land, in four States, 1962 (Wilson and Spencer 1967)

State	Growing stock		Sawtimber	
	Million ft^3	*%*	*Million fbm*	*%*
Arizona	5,204	50	22,883	51
Colorado	1,017	10	4,261	9
New Mexico	3,837	36	16,188	36
Utah	434	4	2,019	4
Total	10,492	100	45,351	100

Comparison of Cut to Growth

Low volume cuts in the Southwest are a reflection of the area imbalances of stand-size classes and low per-acre volumes. The cut in Arizona is 68 percent of its growing stock growth and 104 percent of its sawtimber growth (table 3). The appearance that Arizona is overcutting its sawtimber volume is deceptive because of the imbalance in age classes. Growth considerably exceeds harvest, but much of the growth is in trees not yet measurable in fbm. It does, however, contribute greatly to future sawtimber.

The combined cut for the four States equals 59 percent of the growing stock and 90 percent

Table 3.--Net annual growth and cut of ponderosa pine growing stock and sawtimber, in four States, 1962 (Wilson and Spencer 1967)

State	Growing stock			Sawtimber		
	Growth	Cut		Growth	Cut	
	M ft^3	*M ft^3*	*%*	*M fbm*	*M fbm*	*%*
Arizona	84,669	57,558	68	340,022	353,899	104
Colorado	14,992	4,269	28	62,406	23,112	37
New Mexico	40,543	21,587	53	153,582	131,558	86
Utah	6,337	2,390	38	23,371	13,222	57
Total	146,541	85,804	59	579,381	521,791	90

of the sawtimber growth. Arizona and New Mexico combined are cutting 63 percent of their growing stock and 98 percent of their sawtimber compared to 31 and 42 percent respectively for Colorado and Utah. About 89 percent of the sawtimber in Colorado and Utah is under 21 inches in diameter.

Stocking Conditions

Stocking is too low for high timber production in the four States (table 4). Only 3.7 million of the 10.8 million acres of commercial forest land is 70 percent or more stocked. Nearly the same amount (3.8 million acres) has a stocking of 40 to 70 percent, with over 3 million acres having less than 40 percent stocking.

Many stands in the Southwest are overstocked. Reported inventory data reflect area occupancy by stocking classes within stand-size classes, but do not indicate stocking density of individual stands. Half of the forested area classed as 40 percent or more stocked probably contains overstocked stands. Based on this assumption, over 4 million acres may be occupied by stands in which the trees have too little space for optimum growth and are in need of thinning.

Utah forests are in the poorest condition with respect to stocking. Over 46 percent of the

Table 4.--Estimated acreage of commercial ponderosa pine forest land, by stocking classes, within stand-size classes for four States, 1962 (estimates based on proportion of ponderosa pine within data for all types)

Percentage of area stocked by State	Stand-size classes				
	All classes	Sawtimber	Poletimber	Saplings and seedlings	Nonstocked
	M acres				
70 percent or more:					
Arizona	1,515	1,497	9	9	--
Colorado	598	412	184	2	--
New Mexico	1,508	1,438	36	34	--
Utah	128	117	5	6	--
Subtotal	3,749	3,464	234	51	--
40 to 70 percent:					
Arizona	1,516	1,465	30	21	--
Colorado	1,002	734	265	3	--
New Mexico	1,223	1,167	43	13	--
Utah	97	91	5	1	--
Subtotal	3,838	3,457	343	38	--
10 to 40 percent:					
Arizona	563	506	50	7	--
Colorado	462	358	104	0	--
New Mexico	1,409	1,280	75	54	--
Utah	200	195	4	1	--
Subtotal	2,634	2,339	233	62	--
Less than 10 percent:					
Arizona	64	--	--	--	64
Colorado	285	--	--	--	285
New Mexico	194	--	--	--	194
Utah	7	--	--	--	7
Subtotal	550	--	--	--	550
All stocking classes	10,771	9,260	810	151	550

Note: -- means no data available.

ponderosa pine forests of Utah have a stocking of only 10 to 40 percent. Colorado has the greatest number of acres classified as less than 10 percent stocked, with about 12 percent in this category.

HABITAT CONDITIONS

Southwestern ponderosa pine grows under a wide variety of physiographic, edaphic, climatic, and biotic factors. The variation in habitat conditions throughout this zone is too varied to treat here in any great detail.

Clearly, ponderosa pine is quite adaptive to a great range of conditions. Since it occurs under such varied conditions, one would expect important genetic differences relating to its establishment, growth, yield, and quality. Consequently, attempts to transfer progeny from one location to another within the zone may prove unsuccessful and at times quite costly.

PHYSIOGRAPHIC FEATURES

Physiographic conditions exert a strong impact on the establishment and development of the ponderosa pine forest and the harvesting of timber products. The topography is frequently rugged, sometimes too steep to permit harvesting without serious environmental impairment. Other areas present problems due to deeply incised canyons. On the whole, however, most timbered areas can be managed to produce harvestable products.

Geology and Topography

Ponderosa pine occurs in the four major physiographic provinces of the Southwest: (1) the Colorado Plateau, (2) the Southern Rocky Mountains, (3) the Great Plains, and (4) the Basin and Range Provinces (fig. 1). Each province exhibits a uniformity of topographic expression

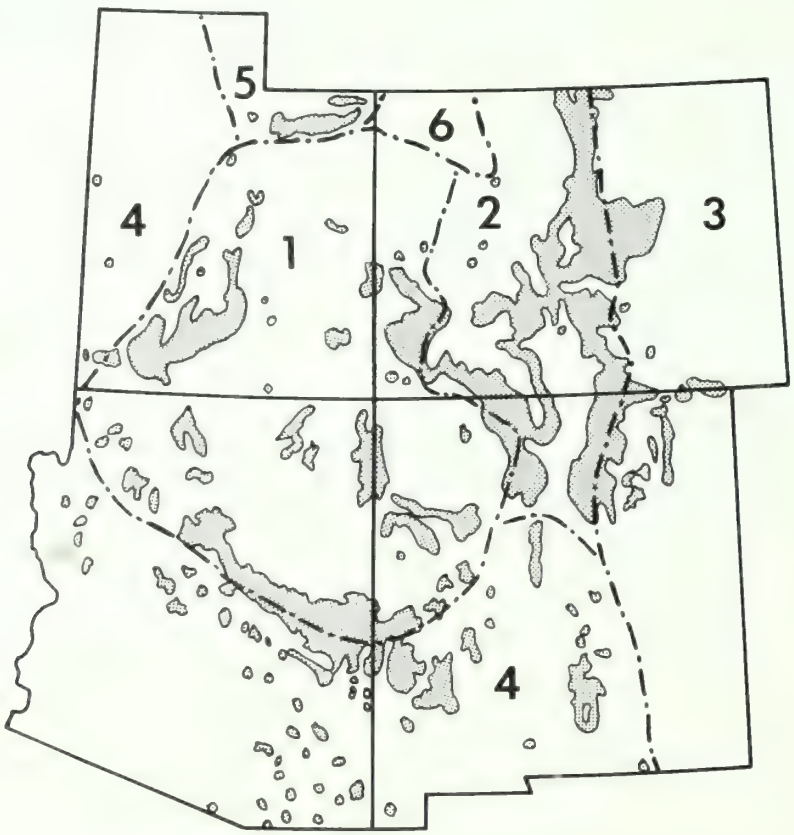

Figure 1.—Physiographic provinces and regions of the Rocky Mountain province for southwestern States.

1. Colorado Plateau
2. Southern Rocky Mountains
3. Great Plains
4. Basin and Range
5. Middle Rocky Mountains
6. Wyoming Basin

in which geologic structure, physiographic process, and stage of development characterize the region (Bowman 1914, Hunt 1967).

Relief and Landform

Elevation

The ponderosa pine cover type in the Southwest occurs primarily between 6,000 and 8,500 ft elevation (Woolsey 1911). At lower elevations it gives way to the pinyon-juniper type and at higher elevations to the mixed conifer type.

Temperatures are most favorable at low elevations and moisture regimes at relatively high elevations (fig. 2) so that highly favorable growing conditions are seldom found. As one factor approaches optimum for ponderosa pine, the other becomes increasingly unfavorable.

Ponderosa pine reaches its best development between 7,000 and 7,800 ft, where it is the climax dominant over large areas. On moister locations, individuals occur in the pinyon-juniper type below 6,000 ft (Kearney and Peebles 1960). Individuals also occur as high as 10,000 ft (Hull and Johnson 1955), mainly on the dry sites in the mixed conifer forest, and sometimes dominate even mesic sites above 9,000 ft following fire.

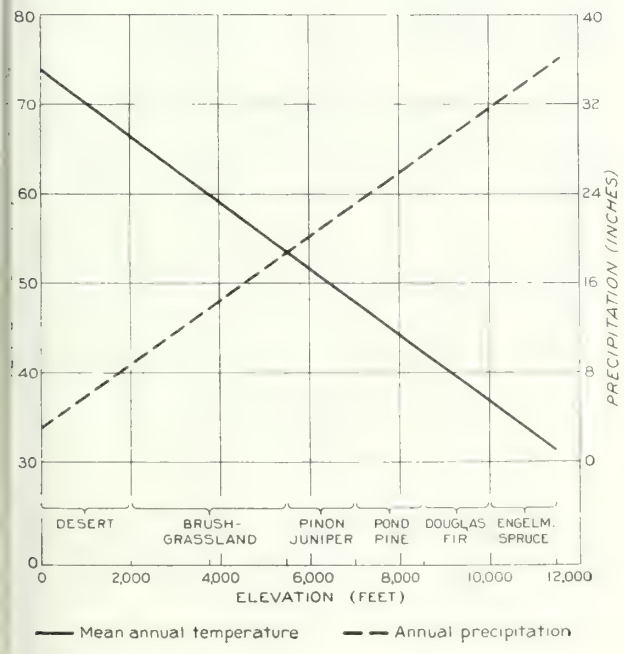

Figure 2.—Temperature and precipitation in relation to altitude in Arizona (Pearson and Marsh 1935).

Strong evaporative winds restrict ponderosa pine from some high plateaus and mesas, even though precipitation is the same as in timbered areas.

Attempts to extend the ponderosa pines into higher or lower elevational zones often end in failures (Pearson 1931). Where irrigation is feasible, ponderosa pines have been successfully planted in the pinyon-juniper type, but without irrigation they usually die the first or second growing season (Pearson 1920).

Slopes

Slope steepness has a strong impact on ponderosa pine due to shallowness and dryness of the soil. Steep slopes, especially when deforested by logging or fire, are generally subject to rapid erosion, rapid water runoff, and very little water penetration and retention. In the ponderosa pine type on the San Francisco Peaks, however, the soils are derived almost entirely from volcanic rocks, contain considerable gravel and rocks, have a high humus surface layer, and are very porous and easily penetrated by tree roots. Water runoff from the Peaks is very low as most of the precipitation sinks into the ground (Martin 1969). Similar situations may occur on other volcanic mountains in the Southwest.

Aspects

Ponderosa pine occurs at higher elevations on south and east aspects than on northern and western exposures. Ponderosa pine, being more drought resistant than Douglas-fir and white fir, can tolerate the drier south slopes, whereas on the wetter north slopes it is replaced by the more shade-tolerant species. At the higher altitudinal limits of the species, temperature becomes more limiting than moisture. Response to these climatic factors related to exposure must be considered in reforestation.

SOIL-TREE RELATIONSHIPS

Southwestern ponderosa pine is not exacting in its soil requirements (Pearson 1931). It grows on a wide variety of soils derived from igneous, metamorphic, and sedimentary rocks. These soils vary considerably in texture, pH, nutrient level, moisture holding and release capabilities, compactness, depth, and other characteristics which have a strong influence on tree establishment and growth. The effects of soil are confounded, to a degree, by the ef-

fects of climate and topography. Soils in the southwestern ponderosa pine type have been studied only in limited areas.

Soil Origin

Soils derived from basalt cover about half of the area in the Southwest forested by ponderosa pine (Lutz and Chandler 1947). The remainder are developed from a great variety of rocks formed during the different periods of geologic history. Soils derived from a given kind of rock will be similar in different areas provided that alterations and the environmental conditions under which weathering occurs are similar (Lutz and Chandler 1947).

Soils derived from igneous and sedimentary rocks are generally more productive than those from metamorphic rocks, but not all igneous and sedimentary rocks produce productive soils. Among the igneous rocks, basalts and granite weather into more productive soils than do the rhyolites; the andesite-diorite group gives rise to soils which are more fertile than those derived from the rhyolite-granite group; and black cinders, which cover sizable areas in the Colorado Plateau in Arizona, generally support sparse stands of timber where the cinders are 4 to 5 ft deep. Shallow cinder soils support tree growth where they are well weathered, underlain by clay, and contain organic material.

Basalt weathers more slowly than granite and gives rise to shallower, rocky soils. On steep slopes basalts often form talus, but if moisture is plentiful, ponderosa pine stands may develop. Reproduction is relatively easy to obtain on deep soils of basaltic and granitic origin. Establishment of reproduction is impossible on deep cinders due to rapid drainage, low field capacity, and extremely high surface temperatures. Where cinder soils are shallow (less than 2 ft) and underlain with clay, seedling survival is strongly correlated with depth of the cinder layer.

Limestone, sandstone, and shale are common in many locations of the Southwest, and produce soils of different productivity. Limestone generally weathers rapidly, particularly the porous and impure varieties. The nature of the developed soil depends on the amount and kind of impurities, since the calcium carbonate is dissolved and removed and the soils are probably more variable than those derived from any other kind of rock (Lutz and Chandler 1947). Soils from very pure limestone may be very poor and are characterized by a high content of fine earth, stoniness, and dryness.

Porous limestone may support poor tree growth due to the rapid drainage of water down cracks and cavities caused by solution of the calcium carbonate.

Limestones in the Southwest contain fair proportions of impurities, weather to deep clay or clay loam soils, and have good underground drainage. Kaibab limestone, one of the top strata at Grand Canyon, is found at surface levels in various parts of the Colorado Plateau in Arizona. Soils derived from it produce the highest volume stands in the Southwest. Some stands east and south of Flagstaff average 35,000 fbm per acre. Soils derived from limestone high in calcite are generally of low productivity.

Soils from weathered sandstones vary in amount of weathering and fertility, depending on the size and chemical composition of individual grains and differences in the amount and composition of the cementing materials (Lutz and Chandler 1947). The more siliceous Coconino sandstone gives rise to soils of lower productivity than sandstones which have a greater amount of calcium carbonate and feldspars. Coconino sandstone is present in many areas where it has been exposed through faulting, or where the Kaibab limestone has been eroded away.

Soils derived from shales are quite variable and usually weather to heavy clay soils of low productivity unless underlain by sedimentary or igneous rocks. These soils occur in the Painted Desert of Arizona, in other parts of the Colorado Plateau, in the Great Plains, and in local areas of the other provinces. Tree cover is generally lacking where the shale soils are deep.

The metamorphic schists, gneisses, and quartzites usually produce poor soils (Bowman 1914). These rocks occur in all the provinces and have only minor importance in the ponderosa pine type.

Soil Texture

Soil texture has been recognized as one of the important factors in tree establishment and growth (LeBarron et al. 1938, Lutz and Chandler 1947, Pearson 1931, Roberts 1939). Deep, moderately sandy or gravelly soils were found to be favorable for tree growth. In general, site quality increased as the proportion of material smaller than 0.2 mm increased. Loam soils are generally more favorable for tree growth than either coarse sands or fine clays. Coarse sandy or cinder soils are relatively poor unless underlain by fine-textured material. Ponderosa pine in Montana had best root development in medium-textured soil and poorest on fine-textured soils (Cox 1959).

Clay soils are generally difficult to regenerate, but they favor good tree development after the seedling stage (Pearson 1931). Clay soils often inhibit germination, particularly where heavy use by cattle or logging equipment have caused compaction.

Soil Structure

Soil structure strongly influences moisture relations, aeration, and root penetration. Most of the soils have good structure except the heavy clay soils. Soil structure is perhaps the most easily damaged of the physical properties and is difficult to repair.

Logging and other woods operations with heavy equipment should not be permitted on fine-textured soils during wet periods, particularly on the heavier clay soils. These soils are easily compacted, especially when wet, to the point that the soil structure is unsuitable for tree establishment. Too often, woods operations and heavy use by cattle are not adequately controlled during wet weather.

Soil Depth

Site index is strongly correlated with soil depth (Cox et al. 1960, Myers and Van Deusen 1960, Roberts 1939). Ponderosa pine growth response in Montana was related to soil type, effective soil depth, landform, and moisture availability. High water table on seeps was found to increase site productivity regardless of the soil type or landform (Cox et al. 1960). In the Southwest, shallow soils and high water tables increase the susceptibility of ponderosa pine to heavy windthrow.

Soil depth in the Southwest is extremely variable. In many areas, the soil mantle is too shallow to support trees except where large cracks occur in the rock formation. Areas with shallow soils on the Colorado Plateau are often underlain by basalt and metamorphic rock. Areas with granite, sandstone, and limestone generally weather rapidly and give rise to deep soils.

Soil Nutrients

Soils in the Southwest generally have adequate nutrients for plant growth (Pearson 1950), although some are deficient in nitrogen and phosphorus for adequate top and root growth. Some studies are underway to determine optimum nutrient levels to improve survival of seedlings and growth rate of plantation trees, and to stimulate cone production.

Forest fertilization has been tried in some regions. Fertilizers show most potential for improving young mature forest stands and plantations, and for stimulating cone production (Wilde 1958, Schubert 1956a). Root elongation was increased when the level of nitrogen in the soil was brought up to 25 p/m (parts per million) and phosphorus to 5 p/m (Wagle and Beasley 1968). Levels in excess of this amount produced little additional growth. Fertilizer may damage roots, however, if they are in direct contact (Schubert and Roy 1959).

Cone production has been increased by the addition of fertilizers. In California, the addition of ammonium phosphate more than doubled cone production on sugar pines (Schubert 1956a). Similar results were reported for Douglas-fir in the Pacific Northwest (Steinbrenner et al. 1960).

Fertilizer trials with southwestern ponderosa pine were started in 1973. Results of these studies should be available in about 1978.

Changes in soil reaction also affect nutrient availability (Buckman and Brady 1965, Lutz and Chandler 1947).

Soil Acidity

Many forest soils in the Southwest have a near-neutral reaction (Pearson 1931, 1950). Soil pH of some good ponderosa pine sites on the Colorado Plateau ranges from 5.7 to 7.5 (Anderson et al. 1963, Williams and Anderson 1967). Soil reaction of 4.5 to 6.0 has been identified with good quality sites elsewhere (Lutz and Chandler 1947).

Pine seedlings suffer the greatest loss by damping-off fungi when pH exceeds 7.0 (Baxter 1952). Mechanical site preparation which exposes the soil to sunlight may be the only practical silvicultural control method for damping-off in the forest.

Site index and pH are not strongly correlated. This lack of correlation may be due to the rather wide range in pH values normally encountered on good forest sites, and the variability of pH in the rooting zone of site trees. Limiting pH levels are very uncommon.

CLIMATIC REGIME

The climate of ponderosa pine forests in the Southwest is cool and mostly subhumid. The forests occur in a climatic zone between the relatively warm-dry pinyon-juniper or oak woodland types and the relatively cold-moist mixed conifer or lodgepole pine types. Ponderosa pine forest is common only in parts of the

four-State area: in eastern and northern Arizona, in various sections of New Mexico, in southern Utah, in southwestern Colorado, and in the Colorado foothills bordering the Great Plains. Climates of these areas will be discussed briefly here.

Precipitation

Seasonal Distribution

The seasonal pattern of precipitation differs from place to place (table 5). In general, however, winter precipitation, mostly snow, is sufficient that soils are wet at winter's end. Some areas get heavy snows that produce abundant runoff during spring and winter thaws.

The major ponderosa pine areas can be characterized as either dry spring or wet spring areas. Spring is dry in Arizona, southern Utah, southwestern Colorado, and all the pine areas of New Mexico except that which borders the Great Plains in northern New Mexico. Where winter snows accumulate to substantial depths, the impact of dry spring weather is somewhat delayed. In May and June, however, the combination of low precipitation, increasing temperature, largely clear skies, low humidities, and persistent winds bring general drought.

Where spring drought is the rule, it is usually broken by summer rains beginning in July or late June. These rains tend to be lighter and less reliable north of the Grand Canyon. Summer rains commonly begin first in southern New Mexico and last in southern Utah.

Usually, spring is relatively wet in the ponderosa pine forests bordering the Great Plains in Colorado and northern New Mexico. In the northern half of this section, April and May are normally the wettest months (in striking contrast to conditions in Arizona); June is usually drier than May. Frequent showers are likely in July and August.

Drought

At Fort Valley, where precipitation normally exceeds 22 inches, 6 of the 60 years had less than 16 inches of precipitation. June has been the driest month, with only a 47 percent probability of getting a half inch or more of rain (fig. 3). Every month of the year, including the two wettest months of July and August, has had at least four times when less than an inch was recorded. For the ponderosa pine type in Arizona, analysis of 37 years of records indicated only 44 days per year in which the precipitation exceeded 0.10 inch (Green and Sellers

Table 5.--Mean monthly and annual precipitation at 17 stations in major southwestern ponderosa pine areas (values are for 20 or more years unless otherwise indicated)

Station	Elevation	Jan.	Feb.	Mar	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov	Dec.	Annual
	Feet							Inches						
ARIZONA														
Chevlon R.S.	[illegible]	1.49	1.37	1.23	0.87	0.52	0.47	2.78	3.35	1.84	1.67	1.17	1.74	18.50
Fort Valley Exp. Forest	7,347	2.32	2.27	[illegible]	[illegible]	.69	.76	2.65	3.65	[illegible]	1.52	1.14	2.07	22.34
Grand Canyon N.P.	6,950	1.46	1.59	[illegible]	.90	.59	.43	[illegible]	2.06	1.65	1.10	.73	1.51	14.77
Jacob Lake	7,920	1.43	.96	2.10	[illegible]	[illegible]	.86	2.01	2.70	[illegible]	1.71	1.45	2.15	19.07
McNary	7,320	2.18	1.99	2.56	1.22	.66	.69	3.25	3.98	2.34	2.24	1.58	2.76	25.45
COLORADO														
Hautzinger	5,923	.87	1.03	[illegible]	[illegible]	[illegible]	1.94	[illegible]	[illegible]	1.45	[illegible]	1.11	.75	20.82
Monument 2W	7,400	.55	.82	1.46	2.51	2.80	1.65	2.55	[illegible]	1.34	[illegible]	.81	.50	18.55
Pagosa Springs	7,238	2.03	1.61	[illegible]	[illegible]	[illegible]	[illegible]	2.17	[illegible]	1.97	2.38	1.42	1.81	21.09
Red Feather Lakes 2SE	8,237	.61	1.02	1.28	2.39	2.46	1.55	2.08	1.63	[illegible]	1.03	.99	.75	17.28
Tacoma	7,500	[illegible].77	1.21	1.47	1.25	[illegible]	1.02	1.92	2.47	2.34	1.74	1.06	1.41	18.89
NEW MEXICO														
Gascon	8,250	.57	[illegible]	1.43	[illegible]	1.75	1.50	5.08	5.20	1.58	1.82	.81	.93	23.13
Lake Maloya	7,400	.80	[illegible]	1.55	1.50	3.20	[illegible]	3.90	3.11	1.40	1.47	1.43	1.05	22.91
Los Alamos	7,410	.78	.64	.88	[illegible]	1.35	1.38	2.73	3.92	1.89	1.65	.70	.83	17.67
Luna R.S.	7,050	1.04	.80	.76	.62	.48	.73	2.59	2.90	1.71	1.36	.59	.95	14.53
Pueblo 2NNE	6,838	[illegible].91	1.14	1.31	.53	.75	1.98	4.54	4.05	[illegible]	1.20	.74	1.57	21.29
Wolf Canyon	8,135	[illegible].64	1.77	1.90	[illegible]	1.45	1.04	2.91	3.28	[illegible]	1.62	1.16	[illegible]	21.92
UTAH														
Alton	7,040	1.74	[illegible].69	1.46	1.10	.73	.64	1.35	[illegible]	1.38	1.37	.93	1.80	15.80

[1] Monthly averages for 13-15 years.
[2] 19-year averages for August, September, October, and November.

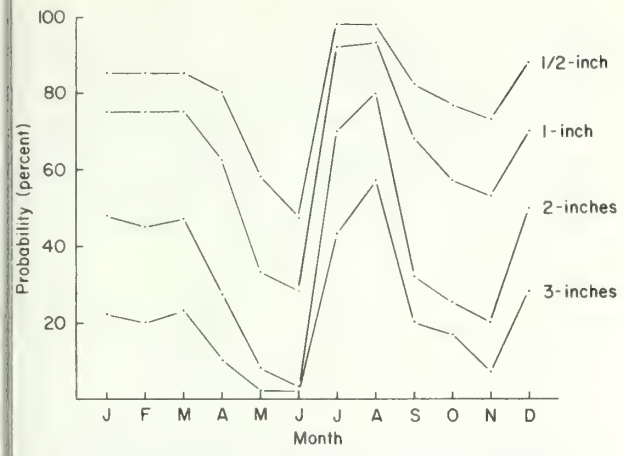

Figure 3.—Probability of getting various amounts of precipitation each month at Fort Valley Station, near Flagstaff, Arizona (Basis 1909-68).

1964). During this period, relative humidity averaged 66 percent at 6 a.m. and 44 at 6 p.m.

Snowfall

Snow cover is extremely important in the ponderosa pine type. It greatly reduces frost heaving. Without enough snow cover to prevent deep soil freezing, new seedlings are likely to be killed by drying. Even older, shallow-rooted trees may be seriously damaged when all soil moisture in their rooting zone is frozen. Where snow accumulates to substantial depth, its lingering presence in the spring delays development of a serious forest fire hazard.

Average annual snowfall for 15 locations in the ponderosa pine forests of Arizona ranged from a low of 12 inches at Painted Canyon in the Basin and Range province to a high of 94 inches at McNary in the Colorado Plateau province, with a mean annual average of 46 inches for all examined locations. Snowfall at these stations is not consistent from year to year. Fort Valley averages 91 inches, yet in 13 out of 60 winters (October 1-April 30), less than 60 inches fell. During 34 percent of these winters, snowfall averaged less than 1 ft per month for 4 consecutive months.

Temperature

Temperatures sometimes drop below 0°F (-18°C), occasionally far below, yet daily highs in winter frequently exceed 40°F (4.4°C). In the summer, afternoon temperatures in Arizona may reach 80°F (27°C) and higher and then drop to 35°F to 40°F (1.7°C to 4.4°C) at night (Kangieser 1966). Similar trends have been reported for Colorado (Berry 1968).

Table 6 summarizes mean monthly temperatures for the pine type in different parts of the Southwest. Various temperature parameters for Fort Valley (fig. 4) summarize the temperature climate of a fairly representative pine area.

Elevation, slope, aspect, and storms all affect temperature. Temperature at similar elevations in northeastern and southwestern New Mexico differed by only 3°F, while two stations

Table 6.--Mean monthly temperatures in the ponderosa pine type, by physiographic provinces

Month	Colorado Plateau		Basin and Range		Southern Rocky Mountains		Great Plains		Pine type	
	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
January	26	-4	35	2	28	-2	31	0	30	-1
February	29	-2	37	3	28	-2	32	0	31	0
March	35	2	44	6	34	1	38	4	38	3
April	43	6	49	10	41	5	45	7	44	7
May	50	10	57	14	48	9	52	11	52	11
June	60	16	66	19	60	16	63	17	62	17
July	66	19	71	22	64	18	66	19	67	19
August	64	18	68	20	62	17	64	18	65	18
September	57	14	63	17	54	12	57	14	58	15
October	46	8	52	11	46	8	48	9	48	9
November	36	2	43	6	35	2	38	4	38	3
December	26	-3	36	2	27	-3	30	-1	30	-1
Mean annual	45	7	52	11	44	7	47	8	47	8

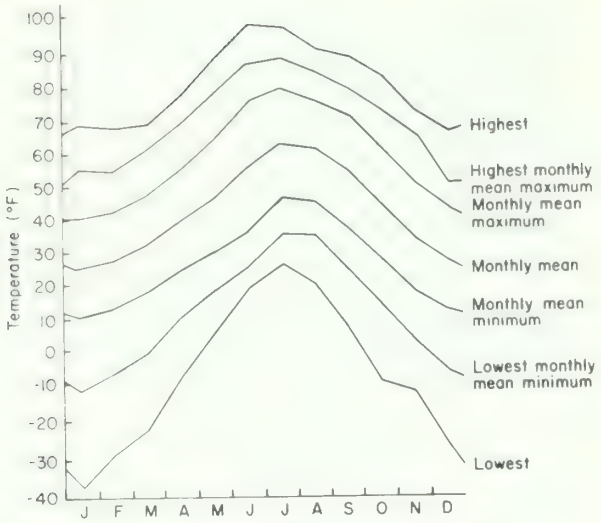

Figure 4.—Highest, lowest, and mean monthly temperature data for Fort Valley Experimental Forest, 1909-68.

only 15 miles apart but differing by 4,700 ft elevation differed by 16°F (Houghton 1972). A north-facing slope in Frijoles Canyon, New Mexico was 13°F cooler than the south-facing slope (Tuan et al. 1969). The average temperatures of west-facing slopes are warmer than the east-facing ones. The average range in daily highs and lows varies from 25°F (14°C) to 35°F (20°C).

Growing Season

The average frost-free period within the pine type is about 135 days, but varies greatly from place to place. Pine seedlings are not killed by 32°F (0°C) temperatures, but growth slows. The variation in frost-free periods between different areas may be related to the problem of planting seedlings raised from offsite seed sources.

EFFECT OF MOISTURE

Precipitation

The seasonal distribution, frequency, and intensity of precipitation are all of critical importance to the establishment and growth of ponderosa pine. Spring planting is more likely to be successful in the southern Rocky Mountains than in the Basin and Range due to the higher precipitation in April and May. Planting on the Colorado Plateau is handicapped by the low probability of rains in spring totaling at least 1 inch. Furthermore, unless the planted trees develop a deep root system, they will have only a slim chance of making it through the winter without adequate protective snow cover.

Winter precipitation is generally sufficient to restore soil moisture to field capacity by early March. However, winters with substantially subnormal snowfall may fail to rewet the entire soil profile, and worsen the effect of a dry spring.

Seed germination during the summer depends on the maintenance of high moisture levels. Although summer precipitation may average about 3 inches per month in July and August, surface soil moisture is often inadequate for seed germination due to the storm distribution pattern. Seeds that germinate in late summer develop into seedlings with only a shallow root system that succumb to fall drought, frost heaving, or winterkill (Larson 1960, 1961, 1963; Schubert et al. 1970).

To be effective, seedfall must coincide with good late spring or early summer rains. These rains do not always occur at opportune times. An outstanding exception in Arizona was the 3.54 inches of rain that fell during May 1919 following the bumper seed crop of 1918. Seed germinated in early June and resulted in the excellent 1919 seedling crop over most of the Colorado Plateau and in some other areas. Similar timing of spring rains can account for the other good seedling years of the past.

Soil Moisture

The moisture-holding capacity of most soils of ponderosa pine forests is sufficient to sustain tree growth (Pearson 1931). Soils derived from basalt and granite, particularly the deeper soils containing fine material, have good moisture retention which may favor the establishment of pine reproduction (Lutz and Chandler 1947). Soils with a high clay content, however, may not release the moisture to the seedling. Limestone soils commonly have good moisture-holding capacity, but some are too porous and drain too rapidly. Reproduction can be difficult to establish on limestone soils, due either to compactness with accompanying poor infiltration or too rapid surface drying, but once established, trees make good growth. Cinders and coarse sandy soils drain too rapidly.

As a general rule, tree roots extend out beyond the edge of the crown to a distance equal to about 70 percent of the tree height. Because soil moisture within this zone may be greatly depleted during dry periods, the possibility of establishing either trees or herbaceous vegeta-

tion is diminished except where tree roots are sparse. The curve of available moisture characterizing the site would probably show a strong positive correlation with distance from the tree to some point at which other factors become dominating. In general, seedlings should not be planted within that distance, or within the root zone of other vegetation.

Infiltration Rates

The influence of soil surface conditions on water infiltration and runoff is well documented (Colman 1953, Kittredge 1948, Lowdermilk 1930, Lutz and Chandler 1947, Rowe 1948, Wilde 1958, and others). Infiltration rates in the ponderosa pine forests of Colorado were found to be 2.4 inches of water per hour for a pine-litter cover compared to 1.9 for pine-grass, and 1.5 for grasslands (Dortignac and Love 1961). The infiltration capacity of forest soils is usually decreased as a result of heavy grazing and repeated burning (Lutz and Chandler 1947). Repeated burning in the chaparral type reduced infiltration rates by 95 percent (Rowe 1948). The thick layer of fine ashes in burned slash piles on the Stanislaus Experimental Forest in California prevented water movement into the soil over a 2-year period (Schubert and Adams 1971). Light burns in Oregon were found to increase percolation rate in the 0- to 3-inch layer but severe burning reduced it (Tarrant 1956). Infiltration rates are also reduced as a result of soil compaction during logging, especially when the soil is wet.

Evaporation

Wind, temperature, exposure, and air humidity all affect the amount of soil moisture lost through evaporation and thereby the amount available for plant growth. Slash reduced moisture loss and was decidedly beneficial in aiding establishment of ponderosa pine seedlings (Pearson and Marsh 1935). Scattering slash rather than burning has been suggested as a measure to conserve soil moisture on light-textured and shallow stony soils (Lutz and Chandler 1947, Pearson and Marsh 1935).

Shade cast by logs, stumps, rocks, and other nonliving material reduces water loss and thereby favors early seed germination and survival of young seedlings (Heidmann 1963b, Schubert and Adams 1971, Schubert et al. 1970). In areas where the soil surface is subject to rapid drying, such as south slopes and large openings, some shade may be essential for seed germination.

Moisture Stress

Moisture stress conditions reduce seed germination and initial seedling development (Larson and Schubert 1969a). Seed germination, root penetration, root dry weight, and cotyledon length decreased as the stress increased beyond 7 bars. Seedlings that germinated under high moisture stresses grew poorly even when watered. New seedlings that developed under high moisture stresses frequently were unable to cast off their seedcoats. Seedlings with their cotyledons tightly encased in the seedcoats rarely survive.

Water balance of pine seedlings varied both with season and treatment. The needle moisture content (NMC) and water saturation deficit (WSD) data indicated that internal moisture stress of needles was low at time of planting and very high during early summer drought (Larson and Schubert 1969b). During this drought period, pine seedlings in unwatered plots containing Arizona fescue and mountain muhly developed greater internal moisture stresses than pines in denuded or watered plots.

Pine needles displayed various symptoms of drought damage. These symptoms were related to NMC as follows: needles green, 150 percent; needles light green, 111 percent; tips of needles brown, 107 percent; needles with purplish cast, 101 percent; needles with necrotic yellow spots, 84 percent; and needles yellow, 55 percent. A needle moisture content (based on ovendry weight) less than 110 percent combined with a WSD greater than 45 percent appears to be the "point of no return" for ponderosa pine seedling survival. Additional studies of moisture stress effects are being made with the "pressure bomb," which measures the internal moisture stress in living plants.

Several methods have been tried to improve moisture relations in ponderosa pine tissue, but none have proved successful. Treatment of ponderosa pine seedling foliage with transpiration retardants had no effect when soil moisture was limiting (Fowells and Schubert 1955, Mowat 1961, Rietveld and Heidmann 1969). Even a three-rock mulch around the base of newly planted trees had no real beneficial effect on pines where competing vegetation had been eliminated (Heidmann 1963b).

Seed Germination

Early germination of ponderosa pine seed is extremely important. The dependence of germination on amount and frequency of rainfall has lead to numerous problems in establishing

seedlings. Seedlings which get started by the third week in July survive best (Larson 1963). Root penetration, number of lateral roots, and seedling dry weight in November were all greatest for seedlings that germinated earliest. Seedlings that started after mid-August were generally killed during the fall drought or by frost heaving before the next growing season.

Seeds sown directly on the ground surface have an extremely poor chance to germinate. Covering the seed with a light layer of soil is highly beneficial. A layer of pine needles also improves germination and survival, especially during dry years (U.S. Department of Agriculture, Forest Service [USDA-FS] 1937). Shade cast by other dead material also aids seed germination at lower elevations where soil moisture is a limiting factor.

Rooting Characteristics

Because ponderosa pine has a deep taproot with long laterals, it can become established and grow under conditions too dry for Douglas-fir, white fir, corkbark fir, blue spruce, and Engelmann spruce. In loosened and watered soil, root penetration to depths of 20 inches or more have been reported for seed that germinated in early July (Larson 1963). Root growth of pine seedlings was uninhibited by grass as long as moisture was kept abundant (Larson and Schubert 1969b).

Ponderosa pine will put down a root to depths of 6 or more ft in porous soils, but seldom more than 3 ft in heavy clay soils. Exceptions occur in soils underlain by rock with deep fissures, where roots have been observed along cut roadbanks at depths of 35 to 40 ft. In open stands, lateral roots may extend 100 ft, while in dense stands they are limited more to the crown width (Pearson 1931). The main mass of roots is concentrated within the top 2 ft of the soil mantle.

In areas with shallow soils or a high water table, ponderosa pine is susceptible to windthrow. The rooting characteristics under these situations must be considered in planning harvesting operations to minimize blowdown.

Winterkill

Young ponderosa pines are frequently damaged by severe winter drying (Bates 1923, Pearson 1931). Winterkill occurs when the soil moisture within the root zone is frozen and unavailable to the plant, while the plant continues to transpire and use water.

Trees are particularly susceptible to winterkill during open winters, especially if day temperatures and winds increase. During 17 of the 60 years of snowfall records at Fort Valley snowfall has averaged less than 12 inches per month from the first of November to the end of February. During these relatively open winters soil freezes to a considerable depth.

Unless the water stress conditions are too severe, only the needles are killed. As long as the buds remain undamaged, the tree will recover during the summer rainy season. Often by fall all the dead needles have been shed and the tree appears healthy. Winterkill can be detected only by examination of the needle whorls. Undamaged trees will have their normal 3-year needle system, while the winterkilled will have only the current needle crop.

Growth of trees damaged by winterkill is probably greatly reduced during the year damage occurred. Growth reduction may be equivalent to at least one annual ring, but such growth losses have not been documented. Any correlation of ring width with drought years should be verified with snowfall records.

EFFECT OF LIGHT

As a general rule, ponderosa pines benefit from all the light they can receive (Tinus 1970). Under field conditions, other factors than light usually prevent or limit their establishment and growth. Ponderosa pines are most influenced by the absence of sunlight during the seedling stage, when young trees may be completely shaded by older trees, shrubs, or grass. Direct sunlight has not been reported to injure young ponderosa pines, except possibly by its indirect effect on temperature, transpiration, and soil moisture. Full utilization of light and heat energy in photosynthesis is restricted by the availability of moisture (Helms 1972, Pearson 1950).

Shade Tolerance

Ponderosa pine is classified as intolerant to shade (Baker 1949). Open stands do not always indicate intolerant species, nor does the occurrence of young seedlings under an overstory prove that they are shade tolerant (Pearson 1931). Some woodland species such as junipers and pinyon are widely spaced because of insufficient moisture to sustain a dense stand. Frequent fires before the advent of fire protection destroyed most young seedlings and saplings and kept the forest open and parklike.

One of the main benefits of shade during the early life of a ponderosa pine is to improve moisture conditions. Shade in itself is not important, since the seeds will germinate in full unlight provided moisture is maintained at dequate levels. Furthermore, pine seedlings hat start under dense shade seldom survive for nore than a few years unless they outgrow the hade or the shade is removed (Pearson 1950). Older trees can survive under conditions of up o 50 percent overhead shade, but both diameter nd height growth are reduced. Height growth s unaffected on trees whose tops receive full unlight.

Stem Form and Branch Characteristics

Young ponderosa pines were found to need ide shade to induce good stem form and fine ranching (Pearson 1940b, 1950). High stand ensities were also thought to be necessary hrough the pole stage to achieve natural prun- ng. Self-pruning has not been found to be trongly correlated with stand density, how- ver. Lower branches die in dense stands, but re retained on trees down to ground level on rees for at least 50 years. Furthermore, trees in he Taylor Woods growing stock levels (GSL) tudy at Fort Valley, growing at a stand density f 200 ft^2 basal area per acre, have a weak, slen- er form and averaged less than 3 inches in iameter at age 40 (Schubert 1971).

Open-grown trees generally, but not al- ways, have a low form factor and coarse ranches. The Taylor Woods GSL study at Fort alley, and others located in the species range, vill provide answers to the relationship be- ween tree form and stand density.

Amount of Light Needed for Full Growth

Light intensity at saturation for ponderosa ine is 12,000 fc (footcandles). A tree is "light- aturated" when a further increase in intensity eases to increase photosynthesis. An increase n light intensity beyond the maximum required nay damage the photosynthetic mechanism Ronco 1970). For comparison, light intensity of ull sunlight on a clear day ranges from 8,000 to 0,000 fc (Tinus 1970) with intensities of 13,000 o 16,000 fc at elevations of about 11,000 ft Ronco 1970). An arc light in a growth chamber as an output of 8,000 to 15,000 fc, while conven- ional fluorescent lamps are rated at 500 to 2,000 c (Tinus 1970). These comparisons take on im- ortance as the production of planting stock hifts from the nursery to the greenhouse.

EFFECT OF TEMPERATURE

Temperature significantly influences height and diameter growth, seed crops, seed germination, and tree mortality. At times temperature may be the limiting factor, but more frequently it exerts an indirect influence. Often it is difficult to isolate temperature from other factors affecting plant responses due to the intricate interrelationships. Many errors in management could perhaps be avoided if we knew more about the effects of temperature on plant and animal life.

Air Temperature

Low temperatures determine the upper altitudinal range of ponderosa pine primarily by limiting growth processes (Bates 1923, 1924; Pearson 1920, 1931). Net photosynthesis of ponderosa pine was found to increase with an increase in air temperature, but the amount of increase would become less as environmental stresses become more severe (Helms 1972). Although moisture conditions improve with a rise in elevation, the average air temperature during the growing season is about 10°F (6°C) cooler in the spruce-fir type than in the ponderosa pine type. This temperature difference may be sufficient to reduce pine growth to permit the spruces and firs to gain dominance.

Top growth of pine was found to be influenced more by air temperature than root temperature. Optimum day temperature for pine top growth is about 74° to 77°F (23°-25°C) (Larson 1967, Tinus 1970). Day temperatures of this magnitude and higher are reached about the end of May and last until about the middle of September.

Soil Temperature

Although soil temperature has been correlated with ponderosa pine growth responses to a lesser degree than either air temperature or soil moisture, it exerts considerable influence on seed germination and tree growth. Southwestern ponderosa pine seeds are noted for their high temperature requirement for germination. The seeds normally do not germinate until the soil temperature reaches 55°F (13°C) even though moisture conditions are favorable (Larson 1961, Pearson 1950). Under field conditions, root growth normally does not start until the soil temperature exceeds 40°F (5°C) (Pearson 1931). Root growth was found to respond more to soil temperature than to air temperature. Best root

growth occurs at a soil temperature of about 74°F (23°C) (Larson 1967).

A study involving the root regenerating potential (RRP) of ponderosa pine in California showed a significantly greater number of seedlings initiated new roots at 68°F (20°C) than at 77°F (25°C) for one seed source, but no significant differences for the other seed source (Stone and Schubert 1959). However, total root elongation was significantly greater at 77°F than at 68°F for both seed sources. Seedlings with the greatest root extension would have a distinct survival advantage in dry areas. The nursery climate was found to have a major influence on the RRP, with the greatest root production associated with the warmest nursery (Schubert and Baron 1965).

Soil temperature data are generally lacking for the southwestern ponderosa pine type. An analysis of soil and air temperature data (Pearson 1931) shows a strong correlation between mean air temperature and soil temperature. Air and soil temperature data were collected during 1917-19 on an area having 25 percent shade from surrounding pines. Soil is a sandy loam derived primarily from basalt. The curves (fig. 5) are intended primarily to obtain an estimate of the soil temperature from mean monthly air temperatures. The growing stock levels study at Fort Valley will furnish soil-air temperature relationships by stand density levels at a future date.

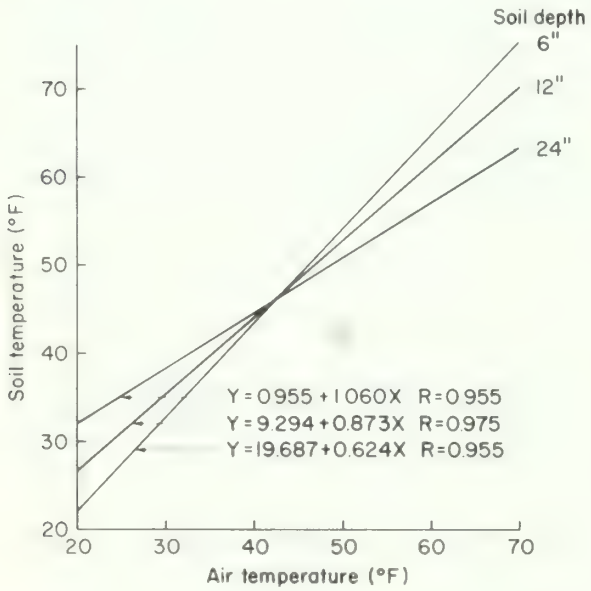

Figure 5.—Relationship of mean monthly soil temperature at three depths to mean monthly air temperature at Fort Valley Experimental Forest, Arizona.

Freezing Injury

Low temperatures normally cause only minor damage (Pearson 1931). Young seedlings are more susceptible than older trees to freezing. Older trees have withstood temperatures of -41°F(-40.6°C) without damage. Freezing injury to young seedlings occurs most frequently in the fall before the seedlings have hardened off and in the spring after growth starts when the temperature drops below 27°F (-3°C) (Schubert 1955, Schubert and Adams 1971).

Shaded seedlings are less likely to be injured (Pearson 1950), while seedlings planted outside their natural habitat are most likely to suffer freezing injury. Pines from nonlocal seed sources were severely damaged in the provenance study at Fort Valley (Larson 1966).

Young ponderosa pine conelets have been killed by late spring freezes (Fowells 1948, Fowells and Schubert 1956), but the amount of damage in the Southwest is unknown.

Frost Heaving

Frost heaving is a serious reforestation problem in the Southwest (Schubert et al. 1970). Loosening of the roots of young seedlings seriously impairs their capacity to survive through the spring and fall droughts (Larson 1960). The degree of overhead shade and the soil surface condition both influence the amount of frost heaving and the ability of the seedling to survive. Soils with a high silt content and high bulk density are especially susceptible to frost heaving.[3] The causes of frost heaving and ways to reduce it are being studied.

Growth Periods

When ponderosa pine begins and ends growth depends on temperature and moisture conditions (Pearson 1918, 1931). Phenologic data for ponderosa pine in the Fort Valley Experimental Forest, collected during 1917-19, were as follows:

Diameter growth starting (tentative estimate)	May 15-30
Vegetative buds swelling	May 1-15
Vegetative buds elongating or opening	May 15-25
Root growth starts	Mar. 15-30
Shoots making rapid growth	June 10-30

[3]*Personal communication from L.J. Heidmann, Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

Needles emerging from papery scales and making rapid growth	June 15-July 30
Shoot growth ceased	July 1-10
Seed germination[4]	July 1-Aug. 30
Staminate buds appearing	May 20-31
Pollen falling	June 10-20
Diameter growth completed (tentative estimate)	Sept. 1-20
Cones full grown	Sept. 15-20
Seeds mature	Oct. 1-20
Needles falling	Oct. 1-30
Root growth stops	Nov. 15-30
Period of active growth	May 15-Sept. 20

The starting dates for diameter growth have not actually been determined, nor has the effect of stand density been related to growth periods. Both beginning and ending dates of diameter growth are important in growth studies. On May 22, 1973, no discernible diameter growth was noted for trees cut on the 30 ft² basal area growing stock level (GSL) plots at Fort Valley. Diameter growth starts about mid-April on ponderosa pine at 6,000 ft elevation in California (Fowells 1941). In most years, diameter growth is completed by the end of August. Growth will continue into late September in some years when both temperature and moisture remain favorable.

Stand density affects start of height growth. At the May 22 date indicated above, trees in the GSL-30 plot had already grown 4 to 6 inches, whereas trees in the adjacent unthinned plot (about 200 ft² basal area) showed no discernible growth. The effect of stand density on growth will be included in the GSL study.

Roots normally grow when soil temperature exceeds 40°F (5°C). From the information shown in figure 5, root growth would vary by rooting depth. It would start about the middle of March when the mean monthly air temperature has reached 33° to 37°F (1° to 3°C) and would stop at the end of November. In years when the ground is covered by snow, and at lower elevations where the average monthly air temperature remains above 35°F (2°C), root growth may continue slowly throughout the winter.

VEGETATION REGIME

Ponderosa pine occurs mainly in the Transition Zone (Merriam 1898), which occupies an altitudinal range from about 6,500 to 8,000 ft, and occurs in the broad climate regime described as warm-moist.

Climax and Succession

Southwestern ponderosa pine occurs as a climax type between 6,000 and 8,000 ft elevation, but disturbance by fire or heavy logging has partially or completely converted many climax ponderosa pine stands to other plant communities (Pearson 1931). The kind of vegetation initially occupying the site usually determines the length of time it will take to return to a ponderosa pine forest. At higher and lower elevations, where ponderosa pine integrates into mixed conifer and pinyon-juniper forests, it loses its climax characteristics.

Stand Conditions

In the Southwest, ponderosa pine forests are usually open grown, and poorly stocked, although many groups are often overstocked. They are interspersed with occasional meadows and parks (Pearson 1931). These forests occur

Figure 6.—Southwestern ponderosa pine occurs mainly as irregular, uneven-aged stands consisting of small even-aged groups.

[4]*Seed germination occurs about 1 week after the summer rains begin and continues until completion or soil temperatures drop below 55° F (13° C).*

mainly as irregular, uneven-aged stands consisting of small even-aged groups, varying in size from a few trees to several acres (fig. 6). Past cuttings, involving a variety of selection methods, have tended to preserve the uneven-aged structure (Myers and Martin 1963a). Occasional stands are even-aged where fires, open areas, and early clearcuttings have regenerated.

Pure ponderosa pine stands occur where the species is climax. One of the largest continuous ponderosa pine forests is found on the Mogollon Plateau, within the Colorado Plateau province, where it extends about 300 miles from central Arizona into western New Mexico. Pure stands of lesser extent are found throughout the ponderosa pine zone. Mixed stands are not common. Both pure and mixed stands may have an understory of younger trees and other herbaceous vegetation. Where stands are dense (a basal area stocking greater than 180 ft^2 per acre) lower vegetation is usually absent, unless shade-tolerant conifers are invading.

The ponderosa pine forests have not yet been classified into habitat types. Such a classification into ecological subdivisions for improved forest description and management has been recognized as a major need. The classification is complicated by past activities which have altered the natural forest stands.

Maintenance of a ponderosa pine cover will be more difficult on some habitat types than on others. Prompt reforestation is essential regardless of habitat type, but some types will present greater challenges. A few habitat types can be used for illustration. Much of the Colorado Plateau could be classified as ponderosa pine-Arizona fescue. If regeneration is not started promptly, the area will convert to grass. Examples can be found near Flagstaff where the ponderosa pine climax has not returned 50 to 100 years after timber harvesting. Parts of the Mogollon Plateau and the Tonto Basin could be classified as ponderosa pine-juniper. Many of these areas are reverting to juniper after harvesting. Much of the San Juan area has a ponderosa pine-Gambel oak type which is being converted following cutting to oakbrush. These areas will require special silvicultural treatments to obtain prompt pine reproduction. Where pine regeneration is initially delayed, conversion to tough competitors may postpone return to pine dominance for many years.

The reverse is also true. The Gila Wilderness has a number of mountain meadows which are converting to ponderosa pine. Overuse by livestock has resulted in deep erosion ditches and a lowering of the water table. Managers are now faced with the problem of halting this change and to restore the site to grass. Other habitat types also present problems requiring research.

EFFECT OF PLANT COMPETITION

All plants within the forest environment compete for moisture, nutrients, and light. This competition varies greatly. The presence of other plants in the ponderosa pine community may at certain stages of development be beneficial and at other times detrimental. Furthermore, not all plants have been studied thoroughly enough to know which ones impede the development of ponderosa pine.

Competition for Moisture

All plants compete for the limited supply of moisture. Competition between ponderosa pine and other species is most detrimental when the trees are young (Larson and Schubert 1969a, 1969b; Pearson 1936, 1942, 1950; Schubert et al. 1970), but it continues throughout the life of the tree (fig. 7). In the early stages, competition is between small pine seedlings and grass, shrubs, and larger trees. In later stages, it is between trees of the same or older age classes.

Some plant species compete more severely than others for moisture (Larson and Schubert 1969b, Pearson 1950). For example, Arizona fescue and black dropseed grow during the spring drought when moisture is critical. However, mountain muhly, blue grama, and most weeds

Figure 7.—Competition for moisture between older trees is often too intensive to permit establishment of an herbaceous ground cover.

do not begin rapid growth until after the start of summer rains when moisture is more abundant. As tree stands develop, competition between trees increases with stand density, and trees with the most extensive root systems have the advantage.

Investigation of the nature and effect of competition between ponderosa pine seedlings and grass has provided growth comparisons and reasons why pines survive and grow better in grass-free environments (Larson and Schubert 1969a, 1969b; Pearson 1950; Schubert et al. 1970). Some of the more pertinent results are: (1) pine seedlings on denuded plots showed an elevenfold greater gain in dry weight than those grown in competition with Arizona fescue and mountain muhly; (2) mountain muhly, a warm-season grower, retarded growth of ponderosa pine seedlings less than did Arizona fescue, a cool-season grower; (3) net gain in dry weight of pines growing with muhly was nearly four times that of pines growing with fescue; (4) grass roots grew 50 percent faster than pine roots; (5) Arizona fescue and mountain muhly were more drought tolerant than ponderosa pine seedlings; (6) grass roots responded faster and more completely than pine roots to rains following the late spring-early summer drought; (7) roots of both grass and pine became dormant as the soil dried out; (8) grass roots resumed growth after rewetting, while most of the pine roots died or remained dormant; (9) grass roots depleted soil moisture to lower levels than did the pine roots; and (10) established pines were able to tolerate competition for moisture by grasses (Larson and Schubert 1969b).

Older trees benefit from reduction in stand density (Schubert 1971). Pine stands thinned to a GSL of 30 ft^2 basal area per acre grew about five times faster in diameter than did unthinned stands with a basal area of 210 ft^2 per acre. Furthermore, ponderosa pine stands thinned to a GSL of 30 produced about 470 pounds forage per acre per year, while unthinned stands produced none (fig. 8).[5]

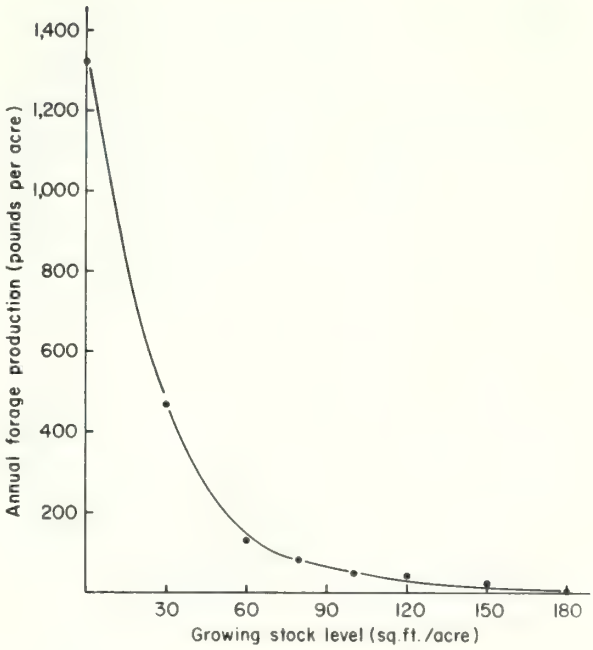

Figure 8.—Annual forage production per acre by tree density level.

Competition for Light and Nutrients

Growth of ponderosa pine decreases as the amount of light is reduced. One of the objectives of thinning is to provide more light for photosynthesis. Pines need about 50 percent overhead sunlight to survive (Pearson 1950). Growth rates have not been correlated with quantity of overhead light. We know that light is only one of the limiting factors, since trees growing at GSL of 80 and lower receive full sunlight, yet their diameter growth rates increase with decreased stand density.

Shade benefits seedlings by conserving moisture; during the pole stage, side shade improves tree form and fine branching (Pearson 1940b).

The nutrient supply in the forest soils is sufficient to maintain tree growth, although growth can often be improved through fertilization (Wagle and Beasley 1968). Competing plants and litter-decaying fungi often deprive ponderosa pine seedlings of needed nutrients, particularly nitrogen and available phosphorus, which are deficient in many soils.

Phytotoxic Effects

Some grass species produce inhibitors that reduce seed germination and seedling growth (Jameson 1961, 1968). Arizona fescue has been identified as one of the grasses containing phytotoxic substances. Ponderosa pine seed covered overwinter with Arizona fescue litter had 63 percent germination, compared to 90 percent for uncovered seed (USDA-FS 1957). Current research indicates that the strongest inhibition occurs in extracts prepared from green foliage and newer litter, and the least

[5]*Personal communication from William Kruse, Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

from older grass litter.[6] Young ponderosa pine roots growing in close association with Arizona fescue and mountain mulhy roots showed no evidence of growth inhibitors (Larson and Schubert 1969b). The inhibitor, identified as a glycoside, most likely breaks down rapidly in well-aerated soils but could accumulate in heavier soils.[6] The seed or seedling must be physiologically active for inhibition to occur, so concentration of inhibitor at time of germination and initial growth is important.

EFFECT OF DAMAGING AGENTS

Southwestern ponderosa pine can be damaged by many agents throughout its life. It is most vulnerable during early life. As the tree reaches maturity, the number of injurious agents decreases, but the damage becomes greater in terms of lost volume.

Snow

Heavy wet snows cause some breakage and bending of trees (Pearson 1950). No data are available on the extent of these types of injury, but they are quite common in young dense stands. In the Taylor Woods GSL plots, heavy wet snows in the spring of 1965 severely bent or broke 12 percent of the trees in the third year after thinning (Schubert 1971). The smaller, weaker trees were damaged most (fig. 9). Almost no damage has occurred since 1965, even though the plots were subjected to the heaviest snowfall on record in December 1967, when 94 inches fell within 9 days.

A partial solution to snow damage in small trees is early thinning of dense stands to strengthen the residual trees. Many of the older trees that are broken are infected with heart rot. These infected trees should be removed in a salvage or improvement cutting.

Wind

Wind is one of the primary causes of damage to ponderosa pine (Myers and Martin 1963b, Pearson 1950). Pearson reported that wind caused 20 to 40 percent of total volume lost over a 30-year period at Fort Valley Experimental Forest. Damage is concentrated in mature and overmature stands during heavy windstorms in the fall in years with heavy precipitation in late

[6]*Personal communication from W.J. Rietveld, Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

Figure 9.—Snow damage in a young stand of ponderosa pine shortly after thinning, Fort Valley Experimental Forest near Flagstaff, Arizona.

September and October (fig. 10). Areas suffering heavy blowdown usually have shallow soils. Damage may also be heavy when strong winds come from the opposite direction of the prevailing winds.

Partial cuttings in the subordinate crown classes have improved windfirmness, particularly in dense stands. Trees with heart rot and low, sharp-angled forks should be cut in a salvage or improvement cut. Residual trees after thinning a tight clump are susceptible to windthrow. All trees with their bases within a foot or so of each other should be cut or all left for the next intermediate cut.

Figure 10.—Ponderosa pines in tight clumps, on shallow soil, and on areas with high water table are susceptible to windthrow if the stand is opened.

Lightning

Lightning kills as many trees as windfall in northern Arizona (Pearson 1950). Unlike windfall, lightning is not always fatal, however. Mature and overmature trees are more frequently killed by lightning than are younger trees. Pearson indicated lightning mortality was rare in stands under 175 years old. Isolated trees or trees with their tops considerably higher than the general crown canopy are prime candidates for lightning strikes. Trees, young or old, that have been struck hard enough to split the bole or loosen the bark seldom survive.

Old overmature, particularly isolated trees should be harvested as rapidly as the allowable cut permits. Hard-hit trees should be cut immediately if merchantable.

Fire

Fire damage occurs mainly in the young age classes such as poles, saplings, and seedlings (fig. 11). Older trees are quite resistant, but hot wildfires will destroy all trees in the burned areas. Many large trees have large fire scars which reduce the value of the butt logs. Fires cause the greatest damage in dense young stands.

Figure 11.—Severe damage by wildfire in October 1948 on the Coconino National Forest, Arizona.

Young dense thickets should be thinned to reduce probability of crown fires. Fuel breaks should be placed along heavily traveled roads, around high-value sites, and at intervals along the contours of steep slopes. Heavily thinned strips, 2 to 3 chains wide, make good fuel breaks. In heavy use areas, thinning slash should be chipped or burned.

Diseases

Various diseases infect ponderosa pine from seedling stage to maturity (Boyce 1961). The more important fall into five main groups: (1) seedling diseases, primarily damping-off, (2) stem diseases such as dwarf mistletoe, limb rust, and Atropellis canker, (3) root diseases such as Armillaria root rot and Fomes root rot, (4) needle diseases such as Lophodermella and Elytroderma needle blights, and (5) stem rots, primarily western red rot.

Seedling Diseases

Damping-off fungi are primarily of importance in nurseries, but also occur in forest soil. Damping-off fungi are not considered a serious forest problem (Pearson 1923), but no assessment has been made. Most damage is confined to first-year seedlings growing in moist, shaded locations in alkaline soils. In nurseries, damping-off can be reduced by treatment with fungicides, by increasing the soil acidity, and by watering early enough to permit drying by evening. No control measures are normally used under field conditions.

Stem Diseases

Dwarf mistletoe is one of the four major causes of mortality in southwestern ponderosa pine (Hawksworth 1961, Myers and Martin 1963b). It has caused up to 36 percent of the mortality on the Fort Valley Experimental Forest (fig. 12). On trees not killed, it is responsible for about 15 percent reduction in growth.

Dwarf mistletoe occurs on about one-third of the commercial acreage (Andrews 1957). It infects trees of all age classes, and may kill trees up to small pole size within a few years of infection (Andrews 1957). Older trees are killed more slowly from the top down until all branches are dead (Hawksworth et al 1968). It has a serious impact on pine seed production,

Figure 12.—Dwarf mistletoe damage on ponderosa pines in the Fort Valley Experimental Forest near Flagstaff, Arizona. The older trees are killed from the top down. Young trees in the vicinity are all infected.

and is reported to reduce seed viability by up to 20 percent (Korstian and Long 1922).

The only methods for reducing dwarf mistletoe are pruning infected branches or killing infected trees (Hawksworth 1961, Hawksworth et al. 1968). Pruning infected branches will eliminate or reduce the parasite on lightly infected trees with no infections near the main stem. Since pruning is expensive, however, and pruned trees may harbor many latent infections, the operation is of limited usefulness. Silvicultural control of dwarf mistletoe is the only practical method of reducing the disease (Hawksworth 1961). The recommended treatment includes the following operations: (1) removal of all infected overstory trees, (2) removal or pruning of all infected trees in the understory, and (3) followup operations in all size classes.

Bole infections are relatively unimportant, and only trees with infection classes of 5 or 6 showed a significant decrease in radial growth (Hawksworth 1961). Trees are rated by lower, middle, and upper thirds of the crown, with a rating of 1 for light and 2 for heavy. Where trees are heavily infected (classes 5 and 6), clearcutting is recommended followed by planting (Heidmann 1968). The shelterwood method may also be applied, since young seedlings under 10 years show little or no infection. Further research is needed on the shelterwood method to determine the impact of dwarf mistletoe on pine seed production and seed viability.

Limb rust kills ponderosa pine throughout the western United States (Boyce 1961, Peterson 1966). It is a systemic disease with the infection spreading throughout the tree. Typically, it kills the branches near the middle of the crown first (fig. 13) and the infection continues in both directions until the tree is dead (Peterson 1966). The rust normally occurs on older trees, and is always fatal (Peterson and Shurtleff 1965). The only control method is removal of infected trees during normal silvicultural operations.

Figure 13.—Mature ponderosa pine infected with limb rust. The disease kills branches near the middle of the crown, and then proceeds in both directions until the tree is dead.

Atropellis canker most frequently damages young ponderosa pines from 5 to 25 years (Boyce 1961). It does not kill trees, but deforms the main stems and branches. Cankered trees have been noted mainly in overcrowded pure stands in the Southwest, but the extent of damage has not been assessed. The disease may be controlled through removal of infected trees during thinning operations.

Root Diseases

Armillaria root rot causes rotting of the bark and wood, and eventual death of weakened trees (Boyce 1961). It is widespread throughout the Southwest, primarily in overmature trees, but is also present in young trees of poor vigor. The fungus is not reported to attack thrifty trees. Visual symptoms are short, yellow needles, abnormal resin flow from the root collar, and decayed bark or wood at the base of the tree. Diseased trees usually occur in clumps, but may be randomly scattered individuals. These trees are very susceptible to wind breakage. The volume lost has not been determined. Control can be achieved through sanitation, salvage, and improvement cuttings.

Fomes root rot also has a widespread distribution, and kills young trees in the vicinity of older infected trees or stumps (Boyce 1961). The fungus spreads from roots of diseased trees to young seedlings. Visual evidence in young killed trees includes the thin, tissue-paperlike mycelium belt between the bark and wood, resin flow from some butts, and conks at the root collar partially hidden by litter. Older trees are susceptible to wind breakage near the butt. Control requires that seedlings not be planted in the vicinity of diseased trees or stumps, and that spacing between planted trees be increased to reduce the possibility of root contacts.

Needle Diseases

Two needle cast diseases occur on young southwestern ponderosa pines. Heavy defoliation reduces tree growth but rarely causes mortality, except of small seedlings. Lophodermella needle blight, locally known as Prescott needle cast, is periodically conspicuous and is known to persist in an area for 15 years.[7] Elytroderma causes needle blight on trees of all sizes from seedlings to mature trees (Lightle 1954). Elytroderma causes "witches' brooms" that badly deform trees and are sometimes mistaken for mistletoe brooms. The only control of Elytroderma is to remove the infected trees, or prune off the infected branches. No control has been reported for Lophodermella.

Stem Rot

Western red rot is the most important heart rot of ponderosa pine in the Southwest (Andrews 1955, 1971). As much as 20 percent of the gross volume in virgin sawtimber stands has been culled because of this rot. It is the most important fungus causing slash decay (Andrews 1971, Boyce 1961).

Harvest cuttings have materially reduced red rot in virgin ponderosa pine sawtimber stands (Andrews 1971). Future cuttings in these stands will progressively reduce the volume of infected wood as the proportion of old trees decreases. Thinnings which favor small-branched and discriminate against large-branched trees also lower the probability of infection. Pruning eliminates future entrance points, as well as branch infections that have not entered the bole. Pruning also creates conditions which inactivate or kill the red rot fungus that may already have extended into the knots. Very little infection occurs in young-growth sawtimber.

Insects

Numerous insects damage ponderosa pines (Keen 1950). Of these insects, the five groups which have done the greatest damage are: (1) bark beetles, which includes the mountain pine beetle, the western pine beetle, the roundheaded pine beetle, the turpentine beetle, and the Arizona five-spined ips;(2) seed and cone insects, primarily pine seed moths and cone beetles; (3) root feeders, primarily root grubs and cutworms; (4) shoot moths, primarily the southwestern pine tip moth and pine shoot moths, and (5) scales, primarily the Prescott scale.

Bark Beetles

The mountain pine beetle is the most aggressive and destructive insect enemy of mature southwestern ponderosa pine (Keen 1952). It normally kills only old, weakened, decadent trees, but during epidemic conditions may also kill young trees. Control measures[8] consist of:

[7] *Personal communication from John Staley, Rocky Mt. For. and Range Exp. Stn., Fort Collins. Colo.*

[8] *Consult forest pest control specialists about details of direct control.*

(1) felling and peeling; (2) felling, piling, and burning; and (3) spraying with insecticides. These three methods must be completed prior to July 15. The two currently registered insecticides are lindane and ethylene dibromide (McCambridge 1972, McCambridge and Trostle 1972). Cacodylic acid (dimethylarsenic acid) has also shown some promise (Chansler et al. 1970, Stevens et al. 1974). Silvicultural control methods involve sanitation-salvage cutting in mature and overmature stands to remove poor vigor trees, and thinning in young stands to remove poor quality and vigor trees.

The western pine beetle mainly attacks trees over 6 inches d.b.h. that are in a weakened condition. It can be controlled through silvicultural treatments such as removal of mature and overmature trees of low vigor, and by thinning sapling and pole stands to improve tree vigor.

The roundheaded pine beetle periodically infests ponderosa pine over thousands of acres in the Southwest. During epidemic periods, infestations develop in dense stands on ridge tops or poor sites or where trees are infested by other bark beetles. They may build up rapidly and spread to stands on better sites. Control measures are the same as for the western pine beetle.

The red turpentine beetle attacks the base of injured, dying, or healthy trees, and freshly cut logs and stumps of southwestern ponderosa pine (Keen 1952). It is not an aggressive tree killer, but frequently weakens trees, making them susceptible to other bark beetles. Their attacks are characterized by large reddish pitch tubes on the lower portion of the trunk, and frass around the base of the tree (fig. 14). The damage is seldom serious enough to warrant control in the forest, but in recreation or other high value areas, the attack can be reduced by cutting out the beetles as soon as pitch tubes form or by chemical treatment indicated for mountain pine beetles.

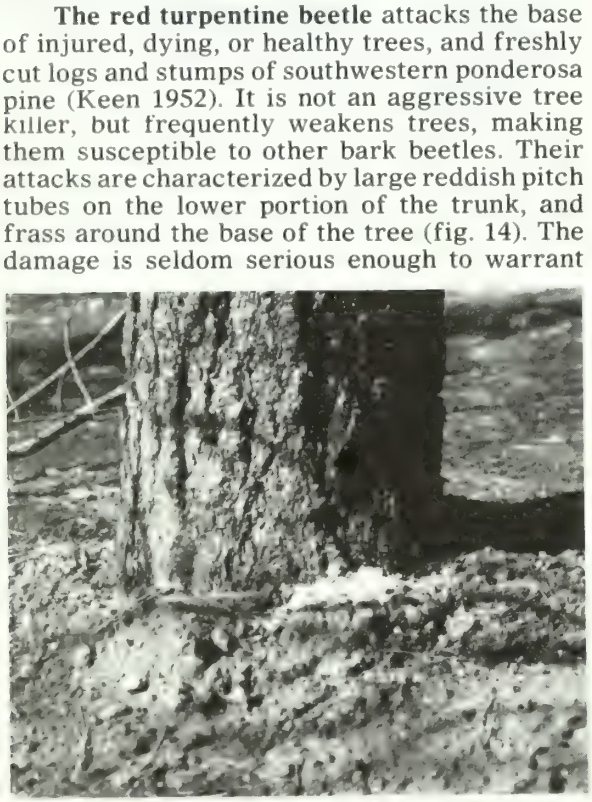

Figure 14.—Frass at base of tree attacked by the red turpentine beetle.

The Arizona five-spined ips attacks young ponderosa pines, and at times is extremely destructive. The beetles prefer fresh slash or injured young trees (Massey 1971). When populations exceed five larvae per ft^2, the adults may kill young, vigorous trees. The beetles are also beneficial, however, in that they help destroy slash. Unless populations are epidemic, the beetles will enter fresh slash and cause little damage. Therefore, one of the "control" methods is to schedule thinnings to provide new slash for the emerging adults. Where this is impractical, ips can be killed by spraying with ethylene dibromide.[8] Cultural controls consist of prompt disposal of all slash 3 inches and larger in diameter by chipping, piling, and burning. Scattering slash in open areas to dry out rapidly, or piling the infested slash and then covering with plastic material, also effectively controls ips. Ips also may be killed when winter temperatures drop below -5°F (-21°C).

Cone Insects

Seed and cone insects have destroyed up to 50 percent of the seed crop in some years (Pearson 1950). In California, seed and cone insects frequently prevent the occurrence of two successive heavy seed years (Fowells and Schubert 1956).

Pine seed moth larvae are found in the axis of pine cones or in seeds (Keen 1958). They bore through seeds, cone scales, and cone axis. In ponderosa pine, from 12 to 100 percent of the cones may be infested and up to 50 percent of the seeds destroyed. Several hymenopterous parasites feed on the larvae. No control methods have been developed.

Cone beetles attack small immature cones in their second year of development, bore into the axis and kill the cones, and then riddle the interior (Keen 1958). Cones attacked by this insect have an aborted appearance. All cones on some trees may be killed. No special control measures are used for cone beetles in forest stands. Insecticides may be used in seed orchards or seed production areas, but timing is critical. Aborted cones which have fallen to the ground may be piled and burned to reduce the insect population. Forest insect control specialists should be consulted for chemical control treatments.

Root Feeders

White grubs (larvae of June beetles) **and cutworms** (larvae of "millers"—night-flying moths) do considerable damage to first- and second-year seedlings (Keen 1952, Pearson 1950, Schubert and Adams 1971). These larvae are generally numerous in most grass-covered areas. They feed on all young tender roots, at times eat entire newly germinated pine seedlings, and can cause complete failure of seeded areas. Clean cultivation is one of the most effective control methods (Schubert and Adams 1971, Schubert et al. 1970). Prolonged drought helps reduce their numbers but may also reduce seedling vigor. Many rodents and birds feed on the larvae. Chlordane is effective against these insects in spot seedings. Severely burned and bare areas generally have too few root-feeding insects to warrant special control measures.

Tree Moths

Tip and shoot moth larvae may severely damage tender new shoots (Keen 1952). The damage to new growth on older trees is considerably less serious than on younger trees. Tip and shoot damage is seldom serious except on trees on cutover lands, plantations, and residential areas where it may be disastrous. Attacks by these insects are evidenced by dead terminals and lateral shoots, and deformed or many-branched trees. The tree may even be killed after heavy repeated attacks. Destruction of the shoots reduces height and volume growth.

Control of these insects is often difficult. The larvae of southwestern pine tip moths leave the tips during July and August and spin cocoons, usually in the bark crevices at the base of the tree below the litter. Here they transform to pupae and pass the remainder of the summer, fall, and winter. The moths fly in late spring and lay their eggs on the branch tips. Control with insecticides requires critical timing during emergence, and expert advice should be sought. Handpicking of infested tips offers some control on small, valuable plantations and special-use areas.

Scale

The Prescott scale often kills branches on southwestern ponderosa pine (Keen 1952, McKenzie 1943, McKenzie et al. 1948). The adults emerge early in the spring and complete their life cycle in 1 year. The females lay their eggs mainly at the first and second nodes from the terminals, and cover the eggs with a white fluffy wax. The larvae feed at the base of needles and in the cracks and crevices of twigs. These scale insects are one of the primary causes of dead branch tips known as flagging.

Pruning the infested branch tips at the third node and then burning may be the only control method needed. The scale has not been reported to kill trees, but at times creates an alarming appearance.

Birds

Carothers et al. (1973) discuss the birds of coniferous forests in northern and eastern Arizona in a collection of four papers.

Many species of birds feed on pine seeds, and some eat buds and newly germinated seedlings. The beneficial aspects of birds outweigh the harmful effects, however. The most beneficial birds feed primarily on insects. The many seed-eaters (Eastman 1960, Smith and Aldous 1947) are nuisances primarily during forest regeneration (Fowells and Schubert 1956, Larson and Schubert 1970, Schubert and Adams 1971, Schubert et al. 1970). Juncos, in one study, destroyed 69 percent of the newly germinated seedlings (Larson 1961). Many other bird species damage newly germinated seedlings when they bite off the seedcoat and the cotyledons.

The only bird control needed may be during direct seeding. Thiram, a nonpoisonous chemical, has been used successfully as a bird repellent (Schubert and Adams 1971).

Two effective methods, both nondestructive, are to cover the pine seed with soil and to coat the seed with aluminum flake or a bright color to discourage seed eating.

Mammals

Many mammals seriously damage ponderosa pine, particularly young trees (Pearson 1950, Schubert and Adams 1971, Schubert et al. 1970). Older trees are damaged by fewer animals, but the results may be just as serious (Keith 1965, Larson and Schubert 1970, Pearson 1950). At least 44 species of mammals feed on conifer seeds (Smith and Aldous 1947).

Small Mammals

Mice, rats, chipmunks, and ground squirrels represent the first real threat to reforestation by seeding (Pearson 1950, Schubert et al. 1970). These rodents consume vast quantities of seed, and injure or kill many young

seedlings from the time they first emerge above the ground surface. Some girdle stems or feed on buds of older seedlings. White-footed and deer mice are the most prolific seed eaters (Fowells and Schubert 1956, Keyes and Smith 1943, Pearson 1950, Schubert and Adams 1971, Schubert et al. 1970). These small rodents are one of the primary reasons why many natural and artificial seedings fail.

Lethal bait has been used to reduce rodent populations, but has not always been effective (Schubert and Adams 1971). Endrin-thiram has been used as a repellent, but the quantity currently permitted by law for seedcoating has been ineffective (Schubert et al 1970). Direct seeding has the best probability of success in years when heavy seedfall on adjacent areas makes an influx of rodents onto the seeded area improbable.

Gophers, rabbits, and hares also do considerable damage in some areas (Pearson 1923, 1950; Schubert et al 1970; Ward and Keith 1962). Pocket gophers confine most of their activity to the root system. In areas with high populations, they may destroy all young seedlings. Rabbits and hares, where abundant, have girdled many young pines (Pearson 1950).

Gophers may be reduced in number by placing strychnine-treated carrots in their tunnels at a rate of 160 to 380 baits per acre (Dingle 1956, Nelson 1960) or by clean cultivation to remove their food supply. Rabbit and hare damage can be reduced by spraying the young trees with a repellent containing thiram (Dietz and Tigner 1968, Hooven 1966, Schubert et al. 1970).

Porcupines have caused serious damage to ponderosa pine (fig. 15) in the Southwest (Pearson 1950). Porcupines do most of their damage on pole-sized trees and young sawtimber, but they also debark or completely girdle seedlings and saplings (Schubert 1970, 1971).

Porcupines are protected by law in Arizona. In special areas, such as seed orchards, a wide metal band around the tree trunk can be used to prevent porcupines from climbing trees. Porcupines have been controlled by placing poison bait in their rest trees or dens (Faulkner and Dodge 1962, Lawrence 1957, Spencer 1950).

Tree squirrels have their greatest adverse impact in destruction of pine cones (Keith 1965, Larson and Schubert 1970). The damage done

Figure 15.—Ponderosa pine severely damaged by porcupines over a period of years.

Figure 16.—Young ponderosa pine severely defoliated by Abert squirrels.

may be significant, though not critical. Red squirrels confine most of their activity to cutting cones, and then caching them for winter food. Abert and Kaibab squirrels cut cones to eat the seed, and clip twigs to eat the inner bark and cambium (fig. 16). These two squirrels do far more damage to ponderosa pine than do the red squirrels. On the Fort Valley Experimental Forest, cone cutting by Abert squirrels reduced cone production 20 percent over a 10-year period (Larson and Schubert 1970). At times, twig cutting by Abert squirrels has been so severe that trees died or were so weakened that insects killed them. Twig cutting also reduces tree growth and causes formation of multiple tops.

Squirrels can be kept out of trees by placing a wide aluminum band around the trunk about 6 ft above the ground. Bands may be required on trees in seed orchards or seed production areas if the damage warrants protective measures. Since squirrels climb to adjacent trees where branches intermingle or jump where branches are close enough, all trees within a group would required bands.

Browsing Animals

Deer, elk, and sheep are generally more destructive than **cattle and horses,** though cattle (fig. 17) in overgrazed stands of young trees may be just as damaging (Cassidy 1937a, 1937b; Cooperrider 1939; Hill 1917; Parker 1948; Pearson 1950). Horses normally cause little damage,

Figure 17.—Cattle damage on ponderosa pine seedlings on the Fort Valley Burn plantation. Nearly 94 percent of the seedlings were browsed or trampled within a few months after planting.

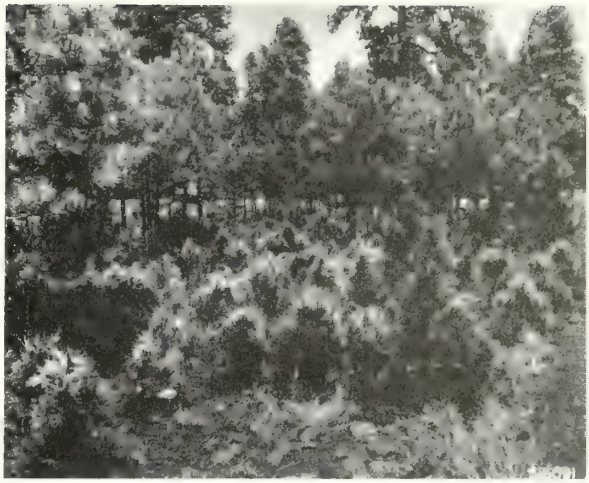

Figure 18.—Fifty-year-old ponderosa pine seedlings of 1919 origin repeatedly and severely "hedged" by deer on the Fort Valley Experimental Forest. Saplings in background are of the same age.

but this may be due to their lower numbers in forested areas. Deer (fig. 18) and sheep (fig. 19), which cause the most serious damage, often do not cause mortality—except of small seedlings—but continuous browsing has stunted larger seedlings for 50 years or more. Many trees, if not damaged too severely or con-

Figure 19.—Ponderosa pine regeneration in foreground destroyed by heavy sheep grazing during early seedling stage. Area in background has an excellent stand of 1914 saplings in a pasture lightly grazed only by cattle and horses (Photo taken in 1936, Fort Valley Experimental Forest, Arizona).

tinuously, recover when the area is closed to grazing or the trees have grown out of reach and make normal growth (Cooperrider 1938).

Deer and elk damage has been reduced by treating trees with repellents containing thiram (Heidmann 1963a). Sheep, cattle, and horse damage is best controlled by fencing to exclude the animals from regeneration areas. Light grazing by cattle may cause little damage during the summer wet season after the seedlings are about 1 ft high.

Logging Damage

Logging damage is the major man-caused mortality factor (Pearson 1950). The damage starts with the construction of roads, and continues with each successive phase of the operation. Young reproduction is damaged or destroyed, and residual merchantable trees injured, by tree felling, skidding, construction of landings and roads, and during slash disposal. Injured trees are often killed by insects. Other serious forms of damage are: soil compaction, especially where logging is permitted during wet weather; erosion channels following skidding; and stream channel damage. There are no actual data on the extent of the damage. On the other hand, many logged areas show little or no damage, even where relatively heavy volumes were removed.

Logging damage can be reduced in many ways. For example: (1) lay out spur roads and skid trails to take maximum advantage of existing openings; (2) do not lay skid trails diagonally downslope; (3) keep stream crossings to a minimum; (4) where live streams are to be crossed, use road fill and culvert instead of fording; (5) fell trees into openings wherever possible; (6) fell trees in a herringbone pattern to spur roads and skid trails; (7) use smallest skid cats needed without dozer blade or with narrow blade; (8) do not hook up to two logs at the same saw cut; (9) do not use residual trees as pivot points for turns; (10) do not permit use of heavy equipment in woods when soil is saturated; (11) keep landings small and take advantage of natural openings; (12) use "hot-logging"; (13) do not permit log hauling during wet weather; and (14) use two-stage cutting for heavy cuts.

SITE QUALITY

Significance

Site class or quality is a measure of the relative productive capacity of an area based on the volume, height, or maximum mean annual increment attained or attainable at a given age. It reflects the effects of the total environment. Classification of land into site quality or productivity classes provides a valuable aid in concentrating and intensifying practices on land with the greatest potential for improved production.

It is important to know site quality, whether management is extensive or intensive. Timber is only one resource the manager must consider. Other resources and uses may justify a more intensive treatment on marginal or submarginal timber lands than could be justified by timber production alone. Measures to protect the land resource and to improve the esthetic quality may be required on all lands, regardless of site quality.

Determination of Site Quality

Site Index

Height, in ft, of dominant and codominant ponderosa pines of average diameter at age 100 years (Meyer 1961) is used as an indicator of site quality (site index) by Forest Survey in the Southwest. The site quality of an area is determined from Meyer's interregional ponderosa pine site index curves. These interregional curves tend to underestimate site quality in the Southwest due to factors which reduce height growth during the seedling-sapling stage. Furthermore, ponderosa pines from the Southwest were not included in the interregional study (Meyer 1961). Site index curves presently

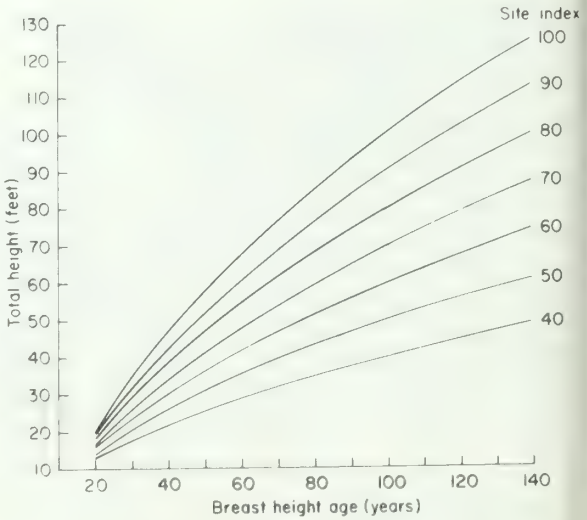

Figure 20.—Site index curves for young-growth ponderosa pine in northern Arizona (Minor 1964).

used in the southwestern States are: (1) Meyer's interregional curves in Utah and western Colorado, (2) Minor's (1964) curves for Arizona and New Mexico, and (3) Mogren's (1956) curves for low-quality sites in the Colorado Front Range.

Minor's site index.—These site index curves (fig. 20) are for dominant trees with breast-height ages of 20 to 140. They cover site index classes 40 to 100 (Minor 1964). These site indices cover the range of age classes planned for the future on National Forests. Some areas may exceed Site Index 100 and may require extension to higher classes. Site indices over 100 can be calculated by means of the equation:

$$S = \frac{H + 1.4003\,(\sqrt{A} - 10)}{1 + 0.1559\,(\sqrt{A} - 10)}$$

where
S = site index,
H = dominant height in ft,
A = age at breast height in years.

To record site index closer than the nearest 10-ft class, the same equation may be used instead of interpolating within the graph.

Dominant trees were selected because of the relative stability within this crown class. "Years-to-breast-height" ranged from 6 to 29 years, with an average of 14.3.

Mogren's site index curves.—Mogren (1956) found that the site index curves developed by Meyer (1934, 1961) did not apply to the adverse ponderosa pine sites on the eastern slope of the Front Range in northern Colorado. The trees on the Front Range were too short to meet even the poorest site class (40 ft at base age of 100 years). His site curves apply primarily to north-central Colorado (fig. 21).

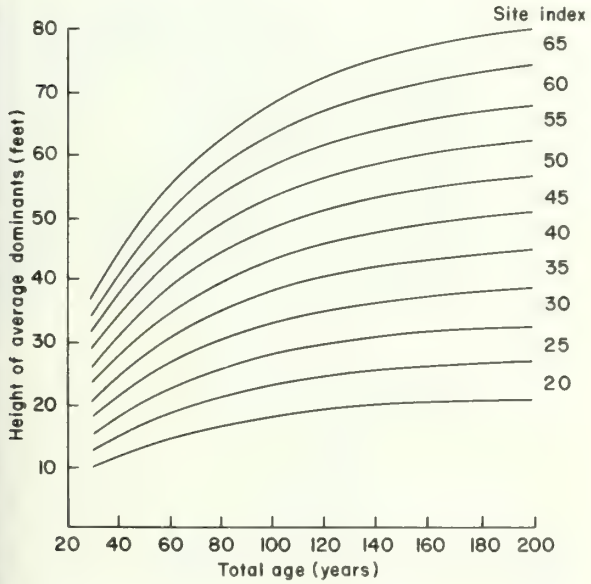

Figure 21.—Site index curves for ponderosa pine, eastern slope of the Front Range in northern Colorado. Reference age: 100 years (Mogren 1956).

Region 3 site classes.—Forested land in Arizona and New Mexico has been grouped for management purposes into three broad site classes using Minor's site indices: Site Class 1 = site index 75 or above, Site Class 2 = site index 55-74, and Site Class 3 = site index 54 or below. Most timber production activity is concentrated on Site Class 1 lands, with some in Site Class 2. Site Class 3 lands are submarginal for timber production. It could be argued that the three site classes are too broad for satisfactory determination of management alternatives.

Timber Suitability Groups

Parts of the Southwest, where intensive surveys have been completed, have been classified into five timber suitability groups in order of their estimated relative productivity potential (Williams and Anderson 1967). The classification is based on soil characteristics, and ties into the R-3 site index. Clary et al. (1966) reported that grouping areas by soil management units and topography reduced the sampling variance for herbage production on areas cleared of timber, and for site index on areas supporting timber.

GROWTH, YIELDS, AND QUALITY

Forest management in the southwestern ponderosa pine type is becoming more intensive. Silvicultural practices are focused on stand manipulation to: (1) improve growth rates by controlling stand density, (2) accelerate replacement by prompt reforestation and increased rate of ingrowth, (3) reduce mortality by removal of high-risk trees, (4) maximize yields by improvement of stocking and by frequent stand re-entry to maintain growth rates, reduce losses, and improve utilization, and (5) improve quality by removal of inferior trees.

GROWTH

Growth rates are a function of site quality and stand density. Growth is determined in terms of diameter, basal area, height, and vol-

ume. Each of these is affected by site quality, stand density, and tree vigor.

Diameter Growth

Trees of all age classes can grow in diameter at about the same rate, provided they are given adequate growing space. Ponderosa pine remains physiologically young and responds to thinning up to an age of at least 200 years (Pearson 1950). Weighted average diameter growth rates in a virgin stand for a 10-year period was 1.14 inches, compared to 1.68 inches in a cutover stand.

Dense stands of slow-growing ponderosa pines have responded well to release (Schubert 1971). Forty-three-year-old stands, with an average density of 5,800 stems per acre and an average diameter of 2.6 inches, were thinned in 1962 to test six residual growing stock levels (GSL). The GSL's are numerical indices representing future basal areas when average tree diameter reaches 10 inches or more, and range from 30 to 150 ft^2 per acre. Net diameter growth during the first 5 years after thinning exceeded the prethinning rate by 4.6 times at GSL-30 and 2.2 times at GSL-150 (fig. 22). The effects of thinning on growth rates remained large at the end of 10 years.

Diameter growth was strongly correlated with stand density (fig. 23). For the 10-year period after thinning, 98 percent of the interplot variation in annual diameter growth was associated with stand density. The periodic

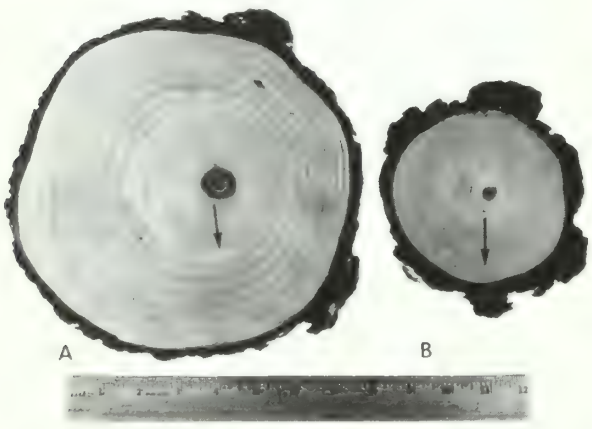

Figure 22.—Growth response of ponderosa pine following stand density reduction in fall 1962, Taylor Woods Growing Stock Level study near Flagstaff, Arizona: **A**, Reduction to 19 ft^2 basal area per acre (GSL-30); **B**, Reduction to 72 ft^2 basal area per acre (GSL-150).

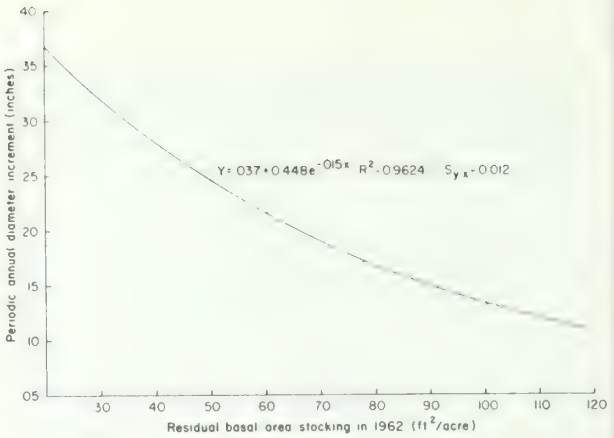

Figure 23.—Relation of periodic annual diameter growth to basal area stocking.

annual diameter increment for the 10-year period is closely estimated by the equation:

$$Y = 0.037 + 0.448e^{-.015x}$$
$$R = 0.981,\ S_{y \cdot x} = 0.012$$

where

Y = increment, in inches,
X = residual basal area immediately after thinning, in ft^2,
e = 2.718 . . . , the base of hyperbolic logarithms.

Both the graph (fig. 23) and the above equation should give useful, if rough, estimates for young stands elsewhere on the Colorado Plateau, and probably throughout the Southwest.

The reduced diameter growth during the last 2 years (fig. 22) may reflect the 1971-72 drought as well as decreasing growing space. The outermost ring is the full annual ring for 1972. This outer ring may appear to be incomplete since the summerwood laid down in late July and August is indistinct adjacent to the bark without staining.

Basal Area Growth

In contrast with diameter growth, net basal area increment was greater at higher residual stocking levels throughout the range of GSL-30 to 150 (fig. 24); at low stocking levels, trees were too few to use the site's full potential for basal area growth. Above GSL-80, increased stocking made less difference.

On the 100 largest trees per acre, however, basal area increment was greatest at GSL-30 and slightly less at each succeeding level to 120, then sharply less at 150.

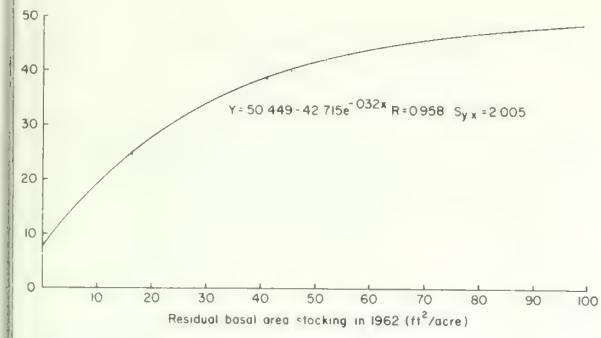

Figure 24.—Relation of periodic basal area growth to basal area stocking.

Basal area increment for the 10-year period after thinning was very highly correlated with stocking level (R = 0.958), and is estimated for the site by the equation:

$$Y = 50.449 - 42.715e^{-0.032x} \qquad S_{y \cdot x} = 2.005$$

where

Y = increment in ft^2 per acre

X = residual basal area immediately after thinning, in ft^2

e = 2.718 . . . , the base of hyperbolic logarithms.

Height Growth

Height growth increases with site quality (Minor 1964, Pearson 1950), but is not affected by stand densities from GSL-30 to 150 (Schubert 1971). Height growth of southwestern ponderosa pine is slow even on the best sites (fig. 25). Growth is most rapid on young trees and then decreases with age. Annual height increment for trees on site index 90 lands is about 1.3 ft at breast height age of 20 years compared to 0.5 ft at 140 years. Trees beyond breast height age of 160 years add very little height growth.

Volume Growth

Volume growth is strongly related to tree size (Pearson 1940a, 1950) and to stand density (Schubert 1971). Total growth in the GSL study increased with stand density except for GSL-150. Annual total volume increment for the four highest growing stock levels, GSL-80, 100, 120, and 150, was essentially the same, however: 50 to 55 ft^3 per acre. For the 100 largest trees, total ft^3 volume increment per acre did not differ significantly for GSL-30 through GSL-120, but dropped significantly at GSL-150. Site index for the study plot was 88, based on Minor's site index which uses age at breast height.

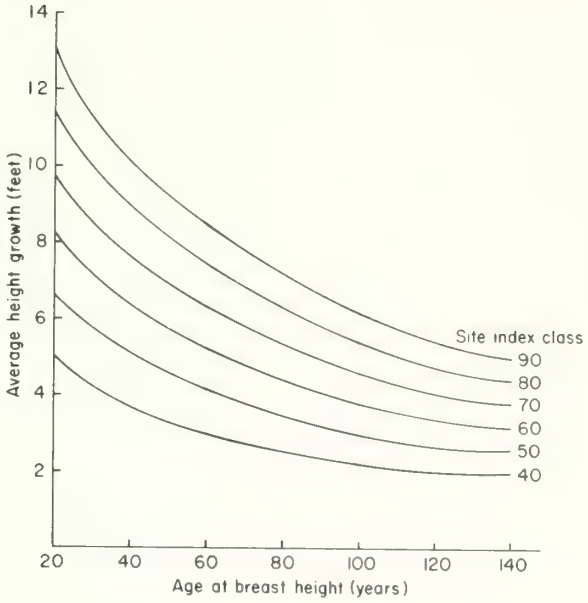

Figure 25.—Approximate periodic annual height growth curves for southwestern ponderosa pine as related to age at breast height and site index.

Increment of merchantable volume on the GSL plots increased significantly for growing stock levels up to 80, but was quite variable at higher stocking levels (Schubert 1971). Analysis of volume added during the 10-year period after thinning has not been completed.

Volume growth needs to be determined for stands of different tree sizes by stocking densities on an array of lands of different site quality. The volume growths cited above were for young, even-aged stands on better-than-average sites.

Mortality

Mortality is highest in unmanaged forests. In southwestern ponderosa pine forests, mortality amounts to about 16 percent of the gross ft^3 volume increment and 18 percent of the fbm increment (Choate 1966, Miller and Choate 1964, Spencer 1966).

Mortality is highly variable. It may amount to half of the gross volume growth. In the G. A. Pearson Natural Area, during the period 1925-50, annual mortality averaged 61 fbm compared to a gross annual growth of 107 fbm per acre (Pearson 1950). Sound silvicultural practices can reduce mortality to a negligible amount (Myers and Martin 1963a, 1963b). Most of the mortality occurs in large trees, generally over 28 inches (Pearson 1940a).

Table 7.--Major causes of mortality of ponderosa pine in the Southwest, by States

State	Growing stock						Sawtimber					
	Fire	Insects	Disease	Weather[1]	Other	Unknown	Fire	Insects	Disease	Weather[1]	Other	Unknown
	- - -

Table 9.--Estimated gross per-acre volume available for harvest at 20-year intervals, by basal area stocking levels, for a ponderosa pine selection forest on areas with site index of 85-90

Basal area stocking (Ft^2/acre)	Stocked stand volume[1]		Volume growth per 20 years[2]	
	All timber	Sawtimber	All timber	Sawtimber
	Ft^3/acre	*Fbm/acre*	*Ft^3/acre*	*Fbm/acre*
30	510	1,620	1,110	4,190
40	680	2,120	1,220	4,560
50	850	2,700	1,230	4,530
60	1,020	3,240	1,190	4,450
70	1,190	3,750	1,160	4,220
80	1,360	4,320	1,110	4,110
100	1,700	5,390	1,010	3,650

[1]Volume needed for full stocking at start of 20-year period.

[2]Gross volume growth based on growth rates of Taylor Woods Growing Stock Level study. These volumes are based on the assumption that average growth rate for each density level will not decrease and that no losses occur.

received several intermediate cuts show a net yield of 103 to 232 fbm per acre. Trees in these stands range up to 300 years in age and over 40 inches in diameter. Stocking densities were not reported.

For rotation periods of 120 years, yields are estimated to be greatest for even-aged stands reduced to a growing stock level of 60 ft^2 per acre every 20 years up to rotation age (table 8). These estimates are based on the assumptions that the average growth rate will remain the same for a 20-year period and there will be no mortality. Stands at higher stocking levels would produce roughly similar ft^3 volumes, but progressively less sawtimber, in the form of more but smaller trees. Since diameter growth is less at greater basal areas, more frequent thinning may be required to maintain the growth rates used for these estimated gross yields.

Annual growth of fully stocked ponderosa pine selection forests should average about 180 to 230 fbm per acre. The estimated 20-year annual yields, based on growth rates in the Taylor Woods plots, show little variation by stand density (table 9), but may be expected to show greater differences by site quality. Estimated 20-year yields, based on growth rates adjusted for stand density and no losses, range from 4,200 fbm per acre for the GSL-30 stand density level to 3,600 for the 100 level. These yields have occurred on the Fort Valley Experimental Forest on a stand basis, but not on a plot basis because of variation in stocking.

Forage Yields

Forage yields in southwestern ponderosa pine forests are less where tree basal area is greater (Clary and Ffolliott 1966, Jameson 1967). Clearings in a forest were found to produce over 600 pounds of herbage per acre compared to under 50 pounds where tree density exceeded 100 ft^2 per acre (fig. 26) (Jameson 1967). At a basal area of 60 ft^2 per acre, forage yields approached their minimum. Total herbage production in the Taylor Woods GSL study decreased as stand basal area increased after thinning.[9] Thinning slash in the Taylor Woods study was lopped and scattered, which may have adversely affected forage production.

Utilization

Scaled volume from timber sales has been 15 to 20 percent below cruised volumes. Some of this difference is due to the difficulty in accurately estimating cull. The remainder represents unutilized wood due to breakage during felling, improper bucking, and merchantable logs left in the woods. The net ft^3 volume of logging residues from saw-log operations in Arizona and New Mexico was found to be about 12 percent of the net product volume (Setzer et al. 1970). Development of new products to utilize low grade timber has improved

[9]*Personal communication from William Kruse, Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

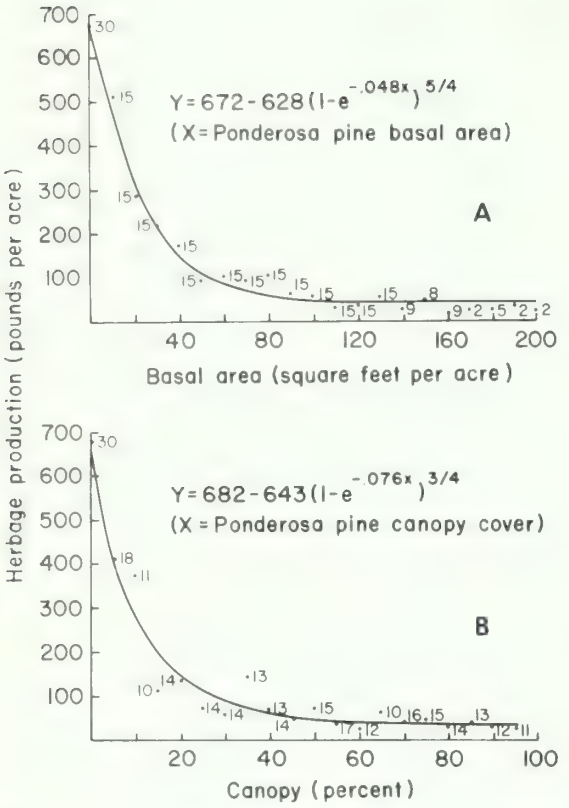

Figure 26.—Relationship of herbage production to stand density **(A)** and crown canopy **(B)** (Jameson 1967).

Figure 27.—"Utilizer" being tested in the Southwest which converts much of the logging residues normally left in the woods into chips for transport to the pulpmill.

utilization (Barger and Fleischer 1964, Mueller et al. 1972). Pulpmills in the Southwest are using logs which were formerly classed as cull. A new approach being studied is to debark and chip small, crooked, or otherwise defective material at the logging site—material constituting much of the volume usually left as slash. The chips are then loaded into a van and hauled to the pulpmill (fig. 27).

Stand Tables

Stand tables for fully stocked even-aged (table 10) and uneven-aged (table 11) ponderosa pine forests indicate the number of trees required by diameter classes. The number of trees present after cutting would remain the same in even-aged stands until the next scheduled cut. After the cut, the number of trees would reflect the change needed to reduce the stocking level to the new residual stand.

Expected future gross stand tables for selection forests reflect the change in number of trees by diameter class resulting from the various growth rates. The example (table 12) is a 20-year projection of table 11, based on growth rates of trees in the Taylor Woods plots. These growth rates are affected by stand density, site quality, climate, and injury, but not by age of the tree under at least age 200. Expected future stand tables may vary by habitat types and other factors not listed here.

Stock Tables

Stock tables are primarily of local value. All the various factors affecting growth will have an impact. Stock tables may have wider application after completion of the habitat classification currently underway. The yields reported here for selection forests were derived from stock tables for residual stands in ft^3 per acre (table 13) and fbm per acre (table 14) and the estimated stock tables in ft^3 (table 15) and fbm (table 16) based on local volume tables developed for site index 85-90.

Volume and Taper Tables

Numerous volume and taper tables have been prepared for southwestern ponderosa pine using scaled volumes and taper of sample trees, graphic methods, and various formulas. Blackjack and old-growth pines of equal heights were found to vary greatly in taper and volume, so separate tables were prepared for the two groups of trees (Hornibrook 1936). Most of

Table 10.--Number of trees per acre, by d.b.h. classes, for various growing stock levels, after thinning an even-aged stand of southwestern ponderosa pine

D.b.h. class (Inches)	Basal area											
	20	30	40	50	60	70	80	90	100	120	150	180
	Number											
1.0	168	252	336	420	505	589	665	757	841	1,009	1,261	1,514
1.5	150	226	301	376	451	526	602	677	752	902	1,128	1,354
2.0	141	212	282	353	423	494	565	635	705	846	1,058	1,269
2.5	130	195	260	324	389	454	518	584	649	779	973	1,168
3.0	120	180	240	300	360	421	480	541	601	721	901	1,081
3.5	111	166	222	277	332	388	443	449	554	665	831	997
4.0	101	151	202	252	302	353	403	454	504	605	756	907
4.5	93	139	186	232	279	325	371	418	464	557	696	789
5.0	86	128	171	214	257	300	343	385	428	514	642	770
5.5	78	117	156	195	235	274	313	352	391	469	586	704
6.0	72	108	144	180	216	252	288	324	360	433	541	613
6.5	66	99	133	166	199	232	265	298	331	398	497	597
7.0	61	92	123	153	184	214	245	276	306	368	459	551
7.5	56	84	113	141	169	197	225	253	282	338	422	507
8.0	52	78	104	130	156	182	208	234	260	312	389	467
8.5	48	72	96	120	143	167	191	215	239	287	359	430
9.0	44	66	88	110	132	153	175	197	219	263	329	395
9.5	40	60	80	100	120	140	161	181	201	241	301	361
10.0	37	55	73	92	110	128	147	165	183	220	275	330
11.0	30	45	61	76	91	106	121	136	152	182	227	273
12.0	25	38	51	64	76	89	102	115	127	153	191	229
13.0	22	33	43	54	65	76	87	98	108	130	163	195
14.0	19	28	37	47	56	65	75	84	94	112	140	168
15.0	16	24	33	41	49	57	65	73	81	98	122	147
16.0	14	21	29	36	43	50	57	64	72	86	107	129
17.0	13	19	25	32	38	44	51	57	63	76	95	114
18.0	11	17	23	28	34	40	45	51	57	68	85	102
19.0	10	15	20	25	30	36	41	46	51	61	76	91
20.0	9	14	18	23	28	32	37	41	46	55	69	83
21.0	8	12	17	21	25	29	33	37	42	50	62	75
22.0	8	11	15	19	23	27	30	34	38	45	57	68
23.0	7	10	14	17	21	24	28	31	35	42	52	62
24.0	6	10	13	16	19	22	25	29	32	38	48	57

these tables were found to apply only to the local area and have found little use in practice. Recently a new series of volume, taper, and related tables were prepared for southwestern ponderosa pine (Myers 1963c). Each table was developed by regression equations which give the highest correlation for the various factors based on regionwide data. These regression equations can be used to prepare local volume and taper tables for young-growth and old-growth ponderosa pine.

Other tables prepared for southwestern ponderosa pine include: (1) taper tables for pole-sized trees which are useful for small product estimates with adjustment for local cull factors due to decay, crook, and fork (Myers 1963a), (2) composite aerial volume tables which give fbm and ft^3 volumes per acre by total height and crown classes (Moessner 1963), (3) pulpwood volume tables which give volumes by total and merchantable height (Minor 1961b), and (4) a simple rapid method for converting basal area to sawtimber volume in fbm, and to merchantable pulpwood volume in ft^3 and rough cords (Minor 1961a).

Yield Prediction

Foresters have the means of evaluating site quality, but have lacked management goals which optimize timber yields within the con-

Table 11.--Number of trees per acre, by d.b.h. classes, for various growing stock levels, for southwestern ponderosa pine selection forest

D.b.h. class (Inches)	Basal area						
	30	40	50	60	70	80	100
	Number						
1	18.0	24.0	30.0	36.0	42.0	48.0	60.0
2	15.0	20.0	25.0	30.0	35.0	40.0	50.0
3	12.3	16.4	20.5	24.6	28.7	32.8	41.0
4	9.9	13.2	16.5	19.8	23.1	26.4	33.0
5	8.2	11.0	13.8	16.5	19.2	22.0	27.5
6	6.6	8.8	11.0	13.3	15.5	17.7	22.1
7	5.5	7.3	9.2	11.0	12.8	14.6	18.3
8	4.5	6.0	7.5	9.0	10.5	12.0	15.0
9	3.72	4.96	6.20	7.44	8.68	9.92	12.40
10	3.03	4.04	5.05	6.06	7.07	8.08	10.10
11	2.52	3.36	4.20	5.04	5.88	6.72	8.40
12	2.07	2.76	3.45	4.14	4.83	5.52	6.90
13	1.71	2.28	2.85	3.42	3.99	4.56	5.70
14	1.39	1.85	2.32	2.78	3.24	3.70	4.63
15	1.15	1.53	1.91	2.29	2.67	3.06	3.82
16	.94	1.26	1.58	1.89	2.20	2.52	3.15
17	.78	1.04	1.30	1.56	1.82	2.08	2.60
18	.63	.84	1.05	1.26	1.47	1.68	2.10
19	.52	.70	.87	1.04	1.22	1.39	1.74
20	.43	.58	.72	.86	1.01	1.15	1.44
21	.35	.47	.58	.70	.82	.94	1.17
22	.29	.38	.48	.58	.67	.77	.96
23	.24	.32	.40	.48	.56	.64	.80
24	.20	.26	.32	.39	.46	.52	.65
Total	100.0	133.3	166.8	200.1	233.4	266.8	333.5

straints of multiple uses. Considerable progress has been made since 1968 to provide the manager with these management tools. Some of the available tools, which will come into greater use as the manager becomes more familiar with them, are:

1. A computer program for simulating the growth of even-aged stands. This permits the manager to evaluate the effects of different growth rates, silvicultural treatments, and catastrophic losses, and to convert these to annual costs and returns on which to base management decisions (Myers 1968).
2. A computer program that analyzes inventory data to determine actual and optimum growing stock, allowable cuts, and other values needed for management planning (Myers 1970). The computed volumes and areas are summarized in a timber management guide to replace the conventional management plan. The computer program will show the effects of cultural operations and other changes for both actual and optimum conditions.
3. Field and computer procedures to develop yield tables for managed stands (Myers 1971). The manager can use these procedures to develop yield tables showing probable results of various management alternatives, to aid in decisionmaking. These yield tables can be made available quickly and at low cost from data obtained from temporary plots.
4. A procedure has been developed for simulating yields of dwarf mistletoe infected even-aged stands of ponderosa pine in Arizona and New Mexico (Myers et al. 1972). Stand age at time of initial infection can be varied as desired. Other control variables, such as stand age at initial thinning, stocking goals, frequency of thinning, and regeneration system, can be varied to arrive at an optimum silvicultural treatment. Since stand condition and severity of dwarf mistletoe infection change with time and in response to

able 12.--Estimated number of trees per acre, by d.b.h. classes, following 20 years' growth of a fully stocked southwestern ponderosa pine selection forest on site index 85-90 for several growing stock levels

D.b.h. class (inches)	Basal area[1]						
	30	40	50	60	70	80	100
	Number						
1	52.0	62.0	69.0	73.0	79.0	84.0	92.5
2	42.8	51.0	56.7	60.0	64.9	68.0	76.0
3	35.1	41.9	46.6	49.3	53.4	55.9	62.5
4	28.9	34.4	38.3	40.5	43.9	45.9	51.4
5	23.7	28.3	31.5	33.3	36.1	37.8	42.2
6	19.5	23.3	25.9	27.4	29.6	31.0	34.7
7	16.0	19.1	21.3	22.5	24.4	25.5	28.5
8	13.2	15.7	17.5	18.5	20.0	21.0	23.4
9	10.84	12.92	14.38	15.22	16.47	17.24	19.28
10	9.91	10.62	11.82	12.51	13.54	14.17	15.85
11	7.32	8.73	9.71	10.28	11.12	11.64	13.02
12	6.02	7.17	7.98	8.44	9.14	9.57	10.70
13	4.95	5.90	6.56	6.94	7.52	7.87	8.80
14	4.06	4.85	5.39	5.71	6.18	6.47	7.23
15	3.34	3.98	4.43	4.69	5.07	5.31	5.94
16	2.74	3.27	3.64	3.85	4.17	4.36	4.88
17	2.25	2.69	2.99	3.16	3.42	3.59	4.01
18	1.85	2.21	2.46	2.60	2.82	2.95	3.30
19	1.52	1.82	2.02	2.14	2.31	2.42	2.71
20	1.25	1.49	1.66	1.76	1.90	1.99	2.23
21	1.03	1.23	1.36	1.44	1.56	1.64	1.83
22	.84	1.01	1.12	1.18	1.28	1.34	1.50
23	.69	.82	.92	.97	1.05	1.10	1.23
24	.57	.68	.75	.80	.86	.90	1.01
25	.47	.56	.62	.66	.71	.74	.83
26	.38	.46	.51	.54	.58	.61	.68
27	.31	.38	.42	.44	.48	.50	.56
28	.26	.31	.34	.36	--	--	.46
29	.22	.25	--	--	--	--	.38
30	.18	--	--	--	--	--	.31
Total	290.83	344.72	373.42	402.93	439.89	462.95	515.26

[1]Based on 20 years' diameter growth by density as follows, for--

30 = 5.5 inches 40 = 4.8 inches 50 = 4.2 inches 60 = 3.7 inches 70 = 3.2 inches 80 = 2.8 inches 100 = 2.2 inches

intermediate cuttings, different treatments or combinations of treatments can be simulated, and the promising ones field tested. This simulation would greatly reduce time-consuming and costly field trials.

The real importance of these tools is their capacity to produce a series of yield tables which show how outcomes will vary in response to changes in cultural treatments and/or variations in original stand or site conditions. They allow the manager to examine the probable results of alternative operations before money is spent on them (Myers 1971).

Allowable Cut

One of the main objectives of forest management is to achieve balance between growth and harvest. Calculation of net growth to arrive at a defensible annual allowable cut has involved many techniques which are often complicated and poorly understood by foresters. The calcu-

Table 13.--Residual ft^3 volume per acre, by d.b.h. classes, for fully stocked southwestern ponderosa pine selection forest on site index 85-90 at several growing stock levels

D.b.h. class (Inches)	Basal area						
	30	40	50	60	70	80	100
	Ft^3						
1	10.8	14.4	18.0	21.6	25.2	28.8	36.0
2	10.5	13.4	16.8	21.1	23.4	26.8	33.5
3	10.5	13.9	17.4	20.9	24.4	27.9	34.8
4	12.5	16.6	20.8	25.0	29.1	33.3	41.6
5	14.3	19.0	23.8	28.6	33.3	38.1	47.6
6	16.1	21.5	26.8	32.2	37.6	43.0	53.7
7	18.0	23.9	29.9	35.9	41.9	47.9	59.8
8	20.0	26.6	33.3	40.0	46.6	53.3	66.6
9	22.0	29.3	36.6	44.0	51.3	58.6	73.3
10	22.2	29.6	37.1	44.5	51.9	59.3	74.1
11	22.6	30.1	37.7	45.2	52.7	60.3	75.4
12	24.7	32.9	41.2	49.4	57.6	65.8	82.3
13	27.3	36.4	45.5	54.6	63.7	72.8	91.0
14	28.4	37.8	47.4	56.8	66.2	75.6	94.6
15	28.7	38.1	47.6	57.1	66.6	76.3	95.2
16	28.8	38.6	48.5	58.0	67.5	77.3	96.6
17	28.5	38.0	47.6	57.1	66.6	76.1	95.1
18	27.2	36.3	45.4	54.4	63.5	72.8	90.7
19	26.3	35.4	44.0	52.6	61.6	70.2	87.9
20	25.2	34.0	42.2	50.4	59.2	67.4	84.4
21	23.6	31.7	39.2	47.3	55.4	63.5	79.0
22	22.1	29.0	36.6	44.2	51.1	58.7	73.2
23	20.8	27.8	34.7	41.7	48.6	55.6	69.4
24	19.4	25.2	31.0	37.8	44.6	50.5	63.1
Total	510.5	679.5	849.1	1,020.4	1,189.6	1,359.9	1,698.9
Merchantable	451.9	602.2	752.3	903.2	1,054.2	1,205.0	1,505.4

lations become particularly difficult when irregular uneven-aged stands composed of small even-aged groups are mixed among essentially even-aged stands.

Complexity can be considerably reduced by recognizing the fact that net growth is equal to present net growth plus the future net growth as altered by management. This net growth (Y) can be calculated for any year after treatment starts (x) using the linear regression equation: $Y = a+bx$, where a = the present net annual growth (G_1) and b = the rate of change in net growth due to management $(G_2 - G_1)/T$ where G_2 is the site potential or estimated future net annual growth and T is the number of years set to complete treatment of the entire forest tract. The net annual growth (Y) can then be calculated for any particular year (t) within the cutting period or cycle by inserting the appropriate volumes. This equation would be: $Y = G_1 + [(G_2 - G_1)/T]\ t$. If the average annual net growth is desired for a particular period, the annual yields derived by the above equation could be summed or obtained by the slightly modified equation: $Y = G_1 + [(G_2 - G_1(/T]\ t/2$.

The volume data for growth may be in either fbm, ft^3, or cords for the total forest tract or on a per-acre basis. If the data are for the entire forest, then the solution of the equation leads directly to the annual allowable cut. If the data are on a per-acre basis, then the average annual net growth must be multiplied by the total tract acreage to get the annual allowable cut.

Data from one of the southwestern ponderosa pine forests will illustrate the computations. Recent inventory data show that the present net annual growth (G_1) is 23 million fbm on a tract of 360,000 acres with a growing stock in sawtimber-sized trees of 1.5 billion fbm. The site potential indicates a future net annual growth (G_2) of 68 million. The plan is to treat the entire forest over a period of 20 years (T), with an equal area treated annually during the

Table 14.--Residual fbm volume per acre, by d.b.h. classes, for fully stocked southwestern ponderosa pine selection forest on site index 85-90 at several growing stock levels

D.b.h. class (Inches)	Basal area						
	30	40	50	60	70	80	100
	Number						
9	4	5	6	7	9	10	12
10	27	36	45	54	64	73	91
11	43	57	71	86	100	114	143
12	66	88	110	132	155	177	221
13	86	114	142	171	200	228	285
14	97	130	162	195	227	259	324
15	105	139	174	208	243	278	348
16	110	147	185	221	257	295	369
17	112	149	186	223	260	297	372
18	112	150	187	224	262	299	374
19	118	158	197	235	276	314	393
20	120	162	202	241	283	322	403
21	119	159	197	237	278	319	397
22	115	150	190	230	265	305	380
23	112	149	186	224	261	298	373
24	107	139	171	208	245	277	346
Total	1,453	1,932	2,411	2,896	3,385	3,865	4,831

cutting period of 20 years (t). Substituting into the above equation yields $Y = 23 + [(68-23)/20] 20/2 = 45.5$ million fbm = annual allowable cut. If the growth data had been converted to an acre basis, the inserted volumes would give $Y = 64 + [(189 - 64)/20] 20/2 = 126.5$ fbm per acre per year. When multiplied by the total 360,000 acres, the annual allowable cut would be 45.5 million, as above.

A more complete discussion of this method for determining the allowable cut, some of the considerations with respect to total growing stock and imbalance of size or age classes, alternative cutting budgets and their effect on growing stock, and on selection of a cutting budget to maximize growth will be covered in a separate report at a future date.[10]

QUALITY

Log quality of southwestern ponderosa pine is low (Choate 1966, Miller and Choate 1964, Spencer 1966). Less than 2 percent qualify as select logs, while nearly 83 percent are low common.

Specific Gravity

Specific gravity has been widely accepted as a major criterion for estimating wood quality (Cockrell 1943, Conway and Minor 1961, Echols and Conkle 1971, Markstrom and Yerkes 1972, Paul 1963, Paul and Meagher 1949, Voorhies 1972). Specific gravity of wood in the six rings formed after thinning in the Taylor Woods GSL study was not significantly different from that in the six rings before thinning.[11] This suggests that wood quality may not have been affected adversely by thinning. Specific gravity of wood after thinning increased as stand density increased, but the average change was only 3.2 percent.

[10]*Larson, Frederic R., and Gilbert H. Schubert. Estimation of allowable cut for southwestern ponderosa pine forests. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.)*

[11]*Alford, Lee T., and Gilbert H. Schubert. Effect of thinning on specific gravity of young ponderosa pine in northern Arizona. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.)*

Table 15.--Estimated future gross total and merchantable ft^3 volume per acre, by d.b.h. classes, following 20 years' growth of a fully stocked southwestern ponderosa pine selection forest on site index 85-90 for several growing stock levels

D.b.h. class (Inches)	Basal area[1]						
	30	40	50	60	70	80	100
	Ft^3						
1	31.2	37.2	41.4	43.8	47.4	50.4	55.5
2	28.7	34.2	38.0	40.2	43.5	45.6	50.9
3	29.8	35.6	39.6	41.9	45.4	47.5	53.1
4	36.4	43.3	48.3	51.0	55.3	57.8	64.8
5	41.0	49.0	54.5	57.6	62.5	65.4	73.0
6	47.4	56.6	62.9	66.6	71.9	75.3	84.3
7	52.3	62.5	69.6	73.6	79.8	83.4	93.2
8	58.6	69.7	77.7	82.1	88.8	93.2	103.9
9	64.1	76.4	85.0	90.0	97.3	101.9	113.9
10	72.7	78.0	86.8	91.8	99.4	104.0	116.3
11	65.7	78.3	87.1	92.2	99.7	104.4	116.8
12	71.8	85.5	95.2	100.7	109.0	114.2	127.7
13	79.0	94.2	104.7	110.8	120.0	125.6	140.4
14	82.6	98.6	109.6	116.1	125.7	131.6	147.1
15	83.3	99.2	110.4	116.9	126.4	132.4	148.1
16	84.0	100.3	111.6	118.1	127.9	133.7	149.7
17	82.3	98.4	109.4	115.6	125.1	131.4	146.7
18	79.9	95.5	106.3	112.3	121.8	127.4	142.6
19	76.3	92.0	102.1	108.1	116.7	122.3	136.9
20	73.3	87.4	97.3	103.2	111.4	116.7	130.7
21	69.6	83.1	91.9	97.3	105.4	110.8	123.6
22	64.1	77.0	85.4	90.0	97.6	102.2	114.4
23	59.9	71.2	79.9	84.2	91.1	95.5	106.8
24	55.3	66.0	72.8	77.6	83.4	87.3	98.0
25	50.8	60.5	67.0	71.3	76.7	79.9	89.6
26	46.0	55.7	61.8	65.4	70.3	73.9	82.4
27	41.5	50.9	56.2	58.9	64.2	66.9	--
28	38.3	45.7	50.1	53.0	--	--	--
29	35.6	40.4	--	--	--	--	--
30	31.5	--	--	--	--	--	--
Total	1,733.5	2,022.4	2,202.6	2,330.3	2,463.7	2,580.7	2,810.4
Merchantable	1,566.4	1,823.1	1,980.8	2,095.8	2,209.6	2,314.0	2,513.1
Residual	451.9	602.2	752.3	903.2	1,054.2	1,205.0	1,505.4
Growth	1,114.5	1,220.9	1,228.5	1,192.6	1,155.4	1,109.0	1,007.7

[1]Based on 20 years' diameter growth by density as follows, for--
30 = 5.5 inches 50 = 4.2 inches 70 = 3.2 inches 100 = 2.2 inches
40 = 4.8 inches 60 = 3.7 inches 80 = 2.8 inches

Fiber Length and Fibril Angle

Both fiber length and fibril angle influence wood quality. In young ponderosa pine, there is a gradual change in fiber length and fibril angle as age increases up to about 50 years (Voorhies 1971). Stresses set up in boards of young ponderosa pine due to excessive longitudinal shrinkage frequently result in warped boards. Some residual trees, even though perfectly vertical, have been found to develop compression wood following partial cutting.[12]

These factors which cause warp and other degrade in wood quality need to be studied as they relate to thinning levels.

[12]*Personal communication from Roland L. Barger, Intermt. For. and Range Exp. Stn., Bozeman, Mont., and Peter F. Ffolliott, Assoc. Prof. of Watershed Manage., Univ. Ariz., Tucson. Research reported was conducted when Barger and Ffolliott were with the Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

Table 16.--Estimated future gross fbm volume per acre, by d.b.h. classes, following 20 years' growth of a fully stocked southwestern ponderosa pine selection forest on site index 85-90 for several growing stock levels

D.b.h. class (Inches)	Basal area						
	30	40	50	60	70	80	100
	Fbm						
9	11	13	14	15	16	17	19
10	89	96	106	113	122	128	143
11	124	148	165	175	189	198	221
12	193	229	255	270	292	306	342
13	248	295	328	347	376	394	440
14	284	340	377	400	433	453	506
15	304	362	403	427	461	483	541
16	321	383	426	450	488	510	571
17	322	385	428	452	489	513	573
18	329	393	438	463	502	525	587
19	344	411	457	484	522	547	612
20	350	417	465	493	532	557	624
21	349	417	461	488	529	556	620
22	333	400	444	467	507	531	594
23	322	382	429	452	489	513	573
24	304	362	400	426	458	480	538
25	285	339	376	400	430	448	503
26	263	319	353	374	402	423	471
27	241	295	326	341	372	388	--
28	225	268	294	311	--	--	--
29	211	240	--	--	--	--	--
30	189	--	--	--	--	--	--
Total	5,641	6,494	6,945	7,348	7,609	7,970	8,478
Residual	1,453	1,932	2,411	2,896	3,385	3,865	4,831
Growth	4,188	4,562	4,534	4,452	4,224	4,105	3,647

[1]Based on 20 years' diameter growth by density as follows, for--
30 = 5.5 inches 50 = 4.2 inches 70 = 3.2 inches 100 = 2.2 inches
40 = 4.8 inches 60 = 3.7 inches 80 = 2.8 inches

Branch Size and Tree Form

Stand density has been reported to affect branch size, natural thinning, and tree form of ponderosa pine (Myers 1963b, Myers and Van Deusen 1960, Pearson 1950). An increase in stand density generally results in reduced stem taper and branch size. Open-grown trees have a tendency to be tapered and coarse branched. Thus the advisability of heavy thinnings has been questioned. Ponderosa pine is also a poor natural pruner. Dead branches frequently remain down to the base of pines, even in dense thickets.

The correlation between branch size and stand density needs to be determined for young-growth ponderosa pine. When should young dense stands be thinned? Is early thinning advisable to get greater diameter growth, if it is achieved at a sacrifice in tree quality (large, coarse branches) or merchantable sawtimber volume (high taper)? Branch size and tree form are inherited characteristics which are sometimes modified by the environment. How much modification of the environment is needed to improve tree quality to an acceptable standard? Answers to these questions will require further study.

Pruning

Wood quality can be improved by pruning, but the costs may be prohibitive. Costs can be kept down by pruning dead branches from potential sawtimber trees immediately after thinning. Live branches can be pruned without significantly affecting growth, provided that at least one-third of the tree height is left in live crown (Heidmann 1963c).

SILVICULTURE AND MANAGEMENT

GUIDING PRINCIPLES

Silviculture and management are interdependent. Silviculture is directed to the creation and maintenance of the kind of forest that will best fulfill the objectives of the manager. The silvicultural prescriptions must be varied to meet the particular needs of the site, the stand, and the land manager.

The practice of silviculture is not limited to growing trees as a crop, but also encompasses growing trees for other purposes, such as natural beauty or outdoor recreation. Silvicultural prescriptions, coordinated through multiple use survey reports or environmental analyses, are the first step toward achieving quality in timber management on National Forests. Management decisions are required on: (1) the form of management, even-aged or uneven-aged, (2) best rotation age for even-aged management, (3) the best stand reentry schedule for stated goals, (4) the kinds and quantities of products needed, (5) the alternative use or combination of uses for each parcel of land, and (6) the combination of goods and services that produce the maximum return.

REQUIREMENTS FOR NATURAL REGENERATION

During the past 60 years, we have learned what it takes to get natural regeneration:

1. A large supply of good seed,
2. On a well-prepared seedbed,
3. Free of competing vegetation,
4. A low population of seedeating pests,
5. Sufficient moisture for early seed germination and seedling growth,
6. And protection from browsing animals and certain insect pests.

The difficulty has been to get these six requirements to coincide. A deficiency of any one of the six may either completely or partially negate any or all of the others. In the excellent seedling year of 1919, most of these requirements were met at least to some degree. During other years, the requirements were reasonably well met in a few areas but not over as widespread an area as in 1919.

Seed Requirements

Seed Supply.—About 200,000 seeds per acre (about 20 pounds) are required to produce 2,000 seedlings for adequate stocking (Pearson 1950). This estimate was based on the assumption that only one seed out of 100 would produce a seedling that survived under moderately favorable field conditions. Under more favorable conditions, about 40,000 to 80,000 seeds would be adequate. In California, seedling survival at the end of the tenth year averaged 22 to 25 percent (Fowells and Schubert 1951).

Cone-bearing trees.—The number of seeds produced by a tree will vary considerably by diameter, age-vigor class, stand density, amount of insect damage or squirrel cutting, and by tree dominance (Larson and Schubert 1970). The large, vigorous, mature trees produce the heaviest cone crops.

Cone production may also vary by tree size at different locations. At Fort Valley and Long Valley Experimental Forests, trees under 16 inches had few to no cones in 1968, while at the Chevelon District on the Sitgreaves National Forest trees 4 to 6 inches in diameter frequently had 40 to 50 cones. The differences in cone productivity may be due to genetic qualities or habitat conditions.

Frequency of cone crops.—Good cone crops were reported on the Coconino and Kaibab National Forests in 1908, 1913, 1918, 1927, 1931, 1936, 1942, 1945, 1954, 1956, 1960, 1965, 1968, and 1971 (Larson and Schubert 1970; Pearson 1923, 1950; Schubert and Pitcher 1973). The only other published records were for the Fremont Experimental Forest in Colorado, which had a good crop in 1926 and 1931 (Roeser 1941). Based on these data, good cone crops may occur at intervals of 3 to 4 years, with lighter crops in some of the intervening years. Annual cone crop reports are needed to determine cone crop frequency by habitat types.

Time of flowering.—Flowering dates of southwestern ponderosa pine have been reported only for central Colorado (Roeser 1941) and north-central Arizona (Pearson 1931). In Colorado, staminate flowers started to open about 2 weeks before the pistillate flowers; pollen release coincided with female bud burst.

For the 9-year study, male flowers opened between May 22 and June 8, while female flowers opened between June 1 and June 25. At the Fort Valley Experimental Forest in Arizona, appearance of staminate buds ranged from May 20 to 31, with pollen shedding between June 10 and 20. Flowering dates may differ in other parts of the Southwest. In California, growth started earlier at the lower elevations (Fowells 1941).

Time of seedfall.—Seedfall at Fort Valley starts about the middle of October, and is about 65 percent complete by the first week of December and 95 percent by the first of April (Larson and Schubert 1970). In some years, seedfall may start earlier in October or be delayed longer into the following year. About 16 percent of the 1960 seed crop fell between July 1 and September 26, 1961. Seeds that fall too late in the summer to germinate will germinate the following year. Strong, dry winds in the fall may cause most of the seed to drop during October and early November (Fowells and Schubert 1956).

Seed dissemination.—Ponderosa pine seeds are not disseminated far from the seed tree (Fowells and Schubert 1956). Based on seedfall rates of 15.2 ft per second in still air (Siggins 1933), seed from the top of a 100-ft ponderosa pine would be blown about 150 ft by a 5 mi/h (mile per hour) wind. A 10 mi/h wind would carry seed about 300 ft. Since the center of the seed mass would be at about 75 percent of the tree height, most of the seed would fall within a distance of one to two times the tree height.

Seed quality.—The largest cone crops produce the best quality seeds (Larson and Schubert 1970). The large crops in 1960 and 1965 produced seeds that were at least 65 percent filled, compared to 10 to 45 percent for the smaller seed crops at Fort Valley. For the 1965 crop, 72 percent of the seeds that fell before December 6 were filled, compared to only 54 percent for seeds that fell after that date.

Seeds per cone.—Cones at Fort Valley averaged only 31 seeds each, with the number of seeds increasing with size of the cone crop (Larson and Schubert 1970). The 5 smallest cone crops during 1956-65 averaged only 14 seeds per cone, compared to 33 for the 5 largest crops. Cones at Long Valley and Chevelon in central Arizona averaged about 76 seeds per cone during the heavy 1968 seed year. Seeds per cone averaged about 70 in California (Fowells and Schubert 1956) and ranged from 64 to 92 in Idaho (Curtis and Lynch 1957).

Seed losses.—Ponderosa pine seed supply may be reduced by insects, birds, mice, and squirrels. Cone beetles have at times destroyed 50 percent of the seed crop (Pearson 1950). Abert squirrels reduce the cone crop by about 20 percent (Larson and Schubert 1970). Data on amounts of seed consumed by birds, mice, chipmunks, and ground squirrels have not been reported. Some flower buds and 1-year-old conelets may also be killed by late June freezes.

Predicting size of cone crops.—The cone crop can be estimated by counting small conelets in the spring with the aid of binoculars, or by checking the twigs cut by squirrels (Larson and Schubert 1970). Since heavy losses may occur the first year of cone development, it is best to make estimates in the spring prior to

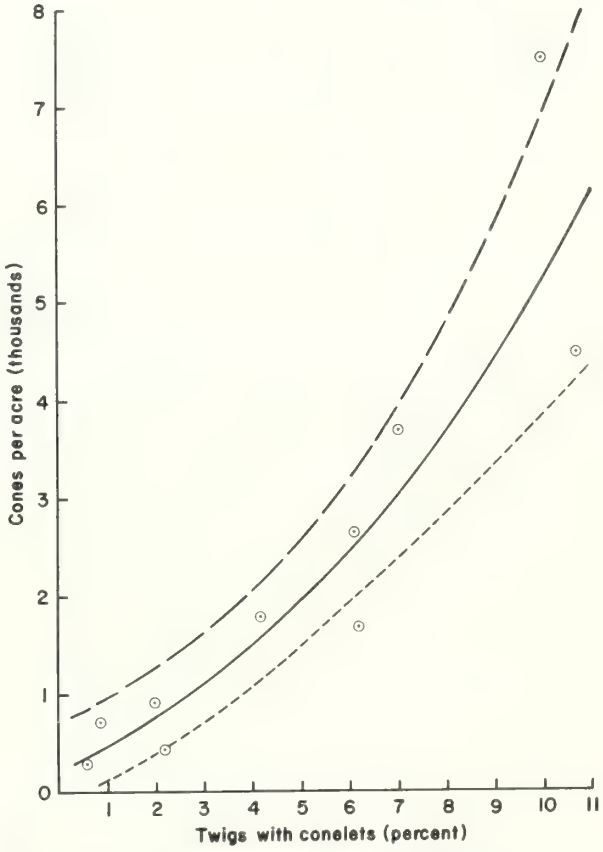

Figure 28.—Relationship between total cone production per acre and the percentage of twigs with conelets found during the spring preceding the maturation of cones. The calculated regression line is $Y = (16.41 + 5.64x)^2$, $F = 47.41$. Dashed lines indicate upper and lower 95 percent confidence limits.

cone maturation. Cone crops may also be estimated from the relationship of cones per acre to twigs with conelets cut by Abert squirrels (fig. 28).

Seed tree specifications.—Healthy, mature trees of large diameter and with exposed crowns are usually the best seed producers (Dunning 1928, Fowells and Schubert 1956, Larson and Schubert 1970). Past fruitfulness, as indicated by the accumulation of old cones under a tree, is a good criterion for choosing seed trees. The best trees to retain for seed production are those that:

1. Are about 24 to 28 inches in diameter,
2. Are dominant or a good codominant if suitable dominant not available,
3. Have a vigor class rating of A or B,
4. Are free from disease or damage,
5. Show evidence of having produced good cone crops,
6. Have straight boles with about 50 percent of tree height in live crown,
7. Have medium to small branches.

Factors Affecting Seed Germination

Moisture.—In Arizona, ponderosa seed seldom germinates until the advent of the summer rains in July. When the summer rains are too light to keep the seeds continuously moist or the rains are late in coming, germination may be delayed until August or early September (Larson 1961, Pearson 1950, Schubert et al. 1970). High moisture stress reduces germination markedly (Larson and Schubert 1969a). In Arizona, seeds have germinated in June when rainfall of 2 or more inches occurred in June or late May. Where spring rains are common, as in the Colorado Front Range, spring germination may be the rule.

Seedbed conditions.—The best seedbed is loose soil with sufficient dead pine litter to facilitate water penetration and seed coverage (Lowdermilk 1930) and to prevent excessive drying of the soil during germination (Krauch 1936, Pearson 1950). Seed coverage is also important because of reduced losses from seed-eating birds and rodents (Pearson 1923, 1950). A loose granular soil was reported to be better than a tight clay soil (Krauch 1956).

Shade.—Ponderosa pine seeds germinate best under partial shade. In the shelterwood study on the Long Valley Experimental Forest south of Flagstaff,[13] germination was highest on plots with a residual basal area of 40 ft^2 per acre and lowest on clearcut plots. Most of the seedlings on the clearcut plots were within the area receiving shade from the trees along the south and west borders.

Factors Affecting Seedling Establishment

Site preparation.—Seedling establishment has been best on areas where competing ground vegetation has been removed and the soil has been loosened. Most failures have occurred on areas which received no site preparation (Larson and Schubert 1969a; Pearson 1923, 1950). Grass was found to be more detrimental than shrubs or trees. Of the grass species, Arizona fescue, bluegrass, and black dropseed were most competitive for soil moisture. These species are all early season growers. Mountain muhly, blue grama, and orange sneezeweed—which make most of their growth during the summer rainy season—have less effect on seedling establishment. Pine seedlings seldom become established in areas covered by dense oak brush.

Competing vegetation may be removed by mechanical, chemical, or burning treatments (Johnsen et al. 1973). Mechanical site preparation is best and can often be accomplished in conjunction with slash disposal. Chemical site preparation has been effective (Heidmann 1967, 1969, 1970), but success has not been universal and present restrictions on herbicides limit their use. Fire has been used to a limited extent, primarily in slash disposal. Fire is not effective on grassy areas or areas covered with sprouting brush.

The best time to prepare the site for natural regeneration is just prior to seedfall. Site preparation at this time provides a loose surface with small depressions into which seed may fall and be covered. The second best is in the fall during or after seedfall. The third choice is during spring and early summer prior to seed germination. Site preparation a year or two in advance of seedfall is generally ineffective.

Shade.—Trees left for seed and shelter should be retained until seedlings are about 1 ft high. Seedlings of this size are flexible. Seedlings over 2 ft in height are often broken during the overstory removal cut.

Grazing.—Livestock should be excluded from regeneration areas until the seedlings are

[13] *Unpublished data on file in study 1203.18, Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

out of danger from browsing. Cattle cause little damage after the seedlings are several feet high if there is sufficient forage available. Trees are most likely to be browsed during the spring and fall drought periods (Cassidy 1937a, Cooperrider 1939, Parker 1948). Light grazing during the summer rainy season may be beneficial by reducing the amount of grass competition. Sheep should be kept out of regeneration areas until the trees are 5 to 6 ft high, and then not permitted to bed down more than one night in the same area (Cassidy 1937b).

REQUIREMENTS FOR ARTIFICIAL REGENERATION

Many of the factors that render natural regeneration ineffective also jeopardize planting and seeding (Pearson 1950, Schubert et al. 1970). Drought during fall combined with abundant competing vegetation is foremost. Where spring normally is dry, ponderosa pine generally germinates only during the summer wet period. If summer drought delays germination into August, the seedlings cannot establish deep roots in the remainder of the growing season. Many of the shallow-rooted seedlings are then heaved by frost during the fall and spring or are winterkilled during open winters. Attrition by soil insects, tip moths, rodents, and browsing animals may be severe for as long as 15 years after initial establishment.

Planting, the most successful method of artificial reforestation, has several advantages over direct seeding. Seedlings are less subject to destruction by rodents and birds. The larger root systems of the seedlings, placed deeply in the soil, are less likely to suffer damage from a fast-drying surface layer. Furthermore, planted trees (1) can begin their season's growth 2 to 3 months earlier, (2) start with a larger root system which continues to develop faster to tap more moisture, and to resist frost action better, and (3) can better withstand partial loss of tops and roots by insects, rodents, and browsing animals than seedlings started from direct seeding.

Seed Requirements

Seed source.—The importance of seed source is widely recognized; many plantation failures have been directly attributed to "off-site" planting stock. Although some exotic species or hybrids may grow better than native species, nonlocal seed sources are not recommended for reforestation projects in the Southwest until their compatibility with local environmental conditions is proved. At Fort Valley, all ponderosa pines from California seed sources died within the first 2 years, while trees from Black Hills and Colorado seed have been subnormal in size and have abnormal stem form (Larson 1966).

Arizona and New Mexico have recently been divided into 10 physiographic-climatic regions, with each further subdivided into five to nine seed collection zones (fig. 29) (Schubert and Pitcher 1973). Provenance tests will be conducted to determine variation and need for adjustment. For the present, seed used for reforestation should be limited to that collected within the local zone.

Seed collection.—Seed should be collected only from trees with good form and vigor, and free of insects and disease. Poor form and excessive limbiness as well as susceptibility to pests may be hereditary. Seed should not be collected from isolated trees because of the strong probability of being self pollinated. Such seeds produce a high proportion of poor-quality progeny. No seed should be collected from plantations of unknown or questionable seed origin.

Cones should be collected only during good seed years. Seeds collected during light seed years may appear fully developed, but they are likely to be self pollinated and of low viability.

Cone collections should not be started until the seeds are mature. The viability of mature seeds is usually high and the derived seedlings are normal. In contrast, the viability of immature seeds may be low, and many of the seedlings may be abnormal and worthless (Schubert 1956b).

Specific gravity of the cones is one of the most reliable indicators of seed ripeness. Maki (1940) found that ponderosa pine cones were mature when they would float in SAE-30 motor oil or kerosene. Kerosene is preferred since its specific gravity of 0.80 coincided with the highest seed viability (Schubert 1956b). Cones were found to open on the tree when the specific gravity dropped to 0.62 (Schubert 1956b). The specific gravity test must be made on freshly picked cones, since detached cones lose moisture rapidly and immature cones would then pass the test.

Cones are frequently collected from squirrel caches. Although viability tests may be high, the unknown seed parentage would generally make this practice inadvisable in a tree improvement program.

Cones should be processed as soon as possible after collection (Schubert et al. 1970). Sacked cones should be kept dry and provided with adequate air space between sacks to pre-

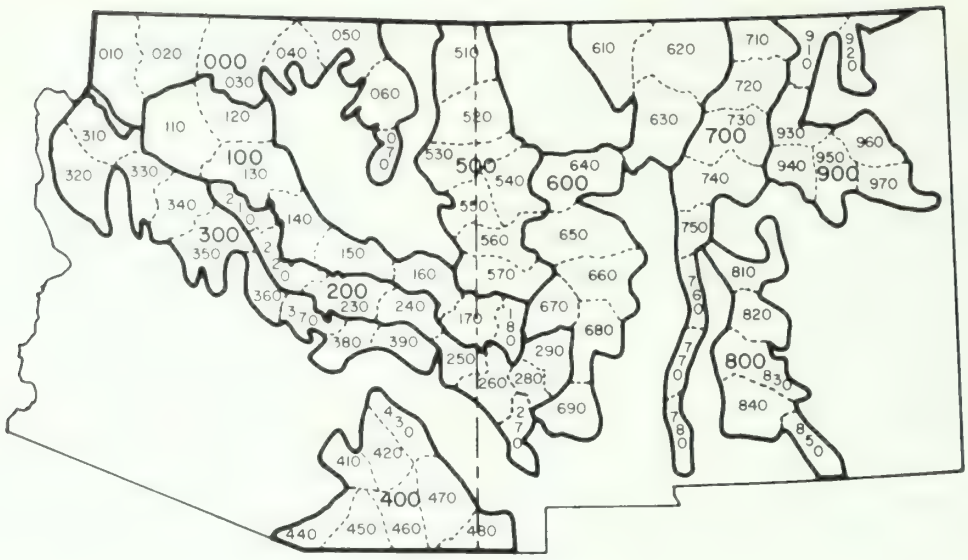

Figure 29.—Seed collection zones for the Southwestern Region (Schubert and Pitcher 1973):

000 Northwest Plateaus (Seed Zones 010-070)
100 Central Plateaus (Seed Zones 110-180)
200 Mogollon Slope and Highlands (Seed Zones 210-290)
300 Central Highlands (Seed Zones 310-390)
400 Southeast Desert Highlands (Seed Zones 410-480)
500 Chuska-Zuni-Gallo Highlands (Seed Zones 510-570)
600 East Continental Highlands (Seed Zones 610-690)
700 East Rio Grande Highlands (Seed Zones 710-780)
800 Sacramento-Guadalupe Range (Seed Zones 810-850)
900 Northeast Plains (Seed Zones 910-970)

vent overheating and molding. Fully mature cones require less predrying, and the seeds are less likely to be damaged during extraction.

Seed storage.—Ponderosa pine seed will maintain high viability when dried to a moisture content of 4 to 8 percent, placed in airtight containers, and stored at 32°F (0°C) or less and preferably at 0°F (−18°C). At least a 4-year supply is needed to keep long-term projects going between seed crop harvests.

Seedling Requirements

Nursery stock.—Planting stock must be in good physiological condition to survive well. Stock for fall planting should not be lifted from the nursery until it has completely hardened off. Stock for spring planting should be lifted before root growth starts.

All planting stock should meet established size and quality specifications (Schubert et al. 1970). A good plantable tree should: (1) have a stem diameter of at least 0.16 inch, (2) have a well-developed top and root system, and (3) be undamaged and free of disease.

Stock shipment.—For short distances, trees are usually transported by unrefrigerated trucks. For long distances, the trees should be shipped by refrigerated trucks, rail, or air. During transit, trees must be kept moist and cool (ideally between 34° and 38°F).

Stock storage.—If trees must be held even for short periods before planting, they should be in a well-ventilated room at a temperature of 34° to 36°F and a relative humidity above 90 percent. Cold storage with controlled temperature and humidity is preferable to heeling-in. Baled trees may be stored in snow. There should be about 2 ft of snow beneath the first tier of bales. Bales (bundles or crates) should be laid about 6 inches apart in the rows with snow packed between them. If more than one tier is required (limit to three tiers), place 6 inches of snow between tiers. Then completely cover stack

with snow. Pick a shaded spot where snow melts slowly. Do not place a tarp over heeled-in trees without providing for ventilation. Trees removed from storage should be limited to 1 day's planting needs, and be kept moist at all times.

Containerized stock.—Containerized seedlings were planted in the summer of 1972 on several National Forests in Arizona and New Mexico. The seedlings were started in styrofoam flats containing 192 holes 1 inch in diameter and 4.5 inches deep. The seedling "plugs" were planted in 4-inch-diameter auger holes.

Seedlings can be grown to plantable size in 6 to 8 months in a controlled-environment greenhouse (Tinus 1972). Costs per thousand surviving trees in the Rocky Mountains were estimated to be $460 for 2-0 bare-root stock and $393 for containerized greenhouse seedlings (Colby and Lewis 1973).

Success of summer plantings depends on early planting and at least moderate, consistent rains during July through September. Success has been hampered by late plantings (August) and sparse, sporadic summer rains followed by a drought in September.

Site Preparation

Thorough site preparation is necessary if planting or direct seeding is to succeed (Schubert et al. 1970). With only partial site preparation, such as scalped spots or narrow cleared strips, more plantations fail than succeed. With few exceptions, plantings on unprepared sites have been failures.

Site preparation involves removing or reducing established vegetation, preparing a good seedbed, removing obstacles to planting, and rendering the sites less favorable for destructive insects and rodents. The most important reason for site preparation in the Southwest is to conserve soil moisture for seedling establishment and early rapid growth (Larson and Schubert 1969a, 1969b; Pearson 1950; Schubert 1970; Schubert et al. 1970). For most sites, mechanical site preparation is best. Chemical site preparation is cheaper and results in higher soil moisture on grass-covered areas provided the grass is deadened (Heidmann 1969).

Planting

Planting ponderosa pine sites has been more successful than direct seeding in the Southwest (Schubert et al. 1970). However, even planted trees die when the job is not done correctly. To establish a successful plantation: plant only healthy, vigorous trees of the local seed source; plant them on well-prepared sites; plant only when the soil is moist; keep the seedling roots moist; do a professional job of planting; and then provide the needed care and protection.

Planting methods.—Seedlings may be planted by hand or machine, depending upon the condition of the site and the availability of equipment. Hand planting in holes dug by auger is preferred to planting in holes dug with handtools. The dibble or planting bar should be used only on light-textured soils because of the difficulty of getting complete hole closure. On suitable areas, machine planting is the easiest, quickest, and most economical method of planting. The machines operate best on level or gentle slopes where the soil contains few large rocks, roots, stumps, and other debris. Heavy-textured soil presents problems, particularly when the soil is too wet to get proper closure of the trench.

Proper attention to details in planting are of greater importance than whether planting is done by hand or machine. Following suggestions given in "Here's How—a guide to tree planting in the Southwest" (Schubert et al. 1969) and "Artificial reforestation practices for the Southwest" (Schubert et al. 1970) will lead to greater planting success.

When to plant.—Spring has been by far the best time to plant (Schubert et al. 1970). Summer planting with containerized stock may be successful, but has not been demonstrated to date. Spring planting should begin as soon as the site is free from snow, and should end about May 15 or sooner if soil does not feel moist and hold together when squeezed in the hand. Summer planting of containerized stock should not begin until soil moisture has been restored to field capacity within the top foot of soil. Fall planting should be delayed until the soil is thoroughly moistened to a depth of 1 ft and the trees have hardened off. South slopes should be planted first in the spring because they are the first to be free of snow and the first to dry out. North slopes should be planted first in the fall because they are the first to become inaccessible when the snows start.

How many trees to plant.—It is recommended that 680 trees per acre be planted at about an 8- by 8-ft spacing. However—and this is important—plant in the best spots, even at the expense of consistent spacing between trees. The number of trees above is based on a survival of 50 percent when the trees attain a diameter

of 5 inches. The 340 5-inch trees are needed for a growing stock level of 80. A different survival rate or different growing stock level would affect the number of trees to plant per acre.

Direct Seeding

Direct seeding, while at least initially more economical and flexible than planting, is less reliable. With a large seed bank, areas can be seeded promptly when the need arises, whereas planting requires 6 to 8 months to produce containerized stock or 2 to 3 years to produce nursery stock. Seeding costs average about one-fourth to one-half planting costs.

Seeding methods.—Regeneration areas may be broadcast seeded, spot seeded, or drill seeded (Schubert et al. 1970). Broadcast seeding, either from the air or ground, is faster than the other two methods, but it has been the least effective and requires the most seed. The effectiveness of broadcast seeding may be improved by preparing a loose seedbed or by disking after sowing. Spot seeding has been the most effective and requires the least amount of seed. The seeds can be placed in more favorable spots and covered with soil to improve germination and reduce losses to rodents and birds. Drill seeding has been tried only a couple of times where site conditions permitted its use. The two small areas drill seeded on the Coconino National Forest gave adequate stocking.

Time to seed.—Where spring is dry, the best time to seed is in late June and early July following a good seed crop the preceding fall. Seeding at this time exposes the seed to rodents and birds for only a short time before the summer rains cause germination. Also at this time, food for rodents and birds is abundant in adjacent areas, thus reducing losses on the seeded site. Where spring is wet, seed should be sown shortly before germination would be expected.

Southwestern ponderosa pine seed does not require stratification (Larson and Schubert 1969a). Furthermore, any advantage of using stratified seeds would be rapidly lost under field conditions, since the seeds gain or lose moisture rapidly to the surrounding media.

Where to seed.—Fresh timber burns and logged areas are the most promising for direct seeding. Frequently, these areas can be seeded without additional site preparation. Fresh burns may pose a serious problem if the hydrophobic ash layer is not broken up. Unless the salvaging logging operation does a good job of breaking up this layer, it is best to use spot or drill seeding.

How many seeds to sow.—The seeding rates will vary considerably, depending on sowing method, seed quality, and specific site. Per-acre rates with good seed range from 1,700 to 4,800 for spot seeding; from 10,000 to 12,000 for drill seeding; and from 16,000 to 48,000 for broadcast seeding on moist, well-prepared areas. Seeding rates for spot seeding were prepared for the California Region (Schubert and Fowells 1964) based on expected stocking for various probabilities of success (fig. 30). The same procedure can be used in the Southwest (Schubert et al. 1970).

Seed origin.—Only seed from the local seed zone should be used in direct seeding (Schubert and Pitcher 1973).

Plantation Care

Successful seeding (natural or artificial) or planting is only the first step in reforestation (Schubert et al. 1970). New plantations must receive care and protection. A mortality of 30 to 40 percent may be expected during the first

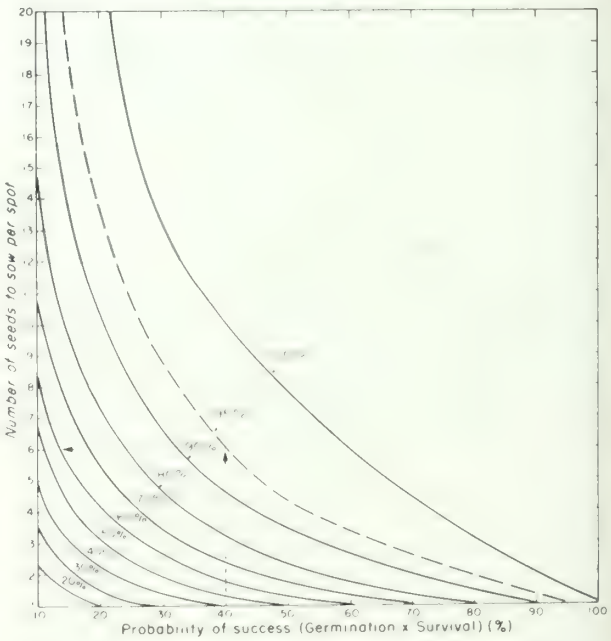

Figure 30.—Expected stocking curves (percent of seedspots with one or more seedlings) for various probabilities of success and sowing rates (Schubert and Fowells 1964). For example, (see dotted line) if you want 95 percent of the spots to have at least one seedling, you should sow six seeds per spot (Schubert et al. 1970).

decade. Mortality may be caused by such physical factors as climate and environment, including fire, or by such biotic factors as insects, disease, animals, or other vegetation. Proper management can greatly reduce the effect of many of these factors. Details of plantation care are fully covered in "Artificial reforestation practices for the Southwest" (Schubert et al. 1970) and under the section "Effect of damaging agents" in this report.

SILVICULTURAL TREATMENTS

Silvicultural treatments must be geared to the needs of the people, but are constrained by site and stand characteristics. These sites, and the stands that grow on them, collectively form the basis for multiple use and sustained yield. The most used silvicultural systems for southwestern ponderosa pine are group selection and shelterwood (Schubert 1973). The existing structure and condition of many stands can be manipulated to produce either even-aged or selection forest. Fortunately, many silvicultural treatments, when based on stand characteristics, also satisfy objectives other than timber production. The treatments must be scheduled and properly coordinated with other uses from the day the stand is first entered and treated through scheduled reentries for intermediate harvest cuts, final harvest, and renewal of the stand.

Stand Condition Classes

The basis for applying any silvicultural treatment in a forest is the condition of the stand. Dunning[14] recognized the need in California for stand condition classification to break away from a uniform treatment of an entire forest or compartment, so that individual groups or stands could be treated according to their specific ecological needs. This need for specific silvicultural treatments by even-aged groups lead Dunning to his "Unit Area Control" concept, as described by Hallin (1951, 1954, 1959).

Stand condition classes are used to describe groups and stands, usually small in area and homogeneous in their attributes. These attributes are described in terms of: (1) age or size of the overstory and understory, (2) species composition, (3) degree of stocking, (4) presence of seed trees, (5) presence of disease, and (6) ground vegetation.

[14]*Personal communication from Duncan Dunning, formerly with Pac. Southwest For. and Range Exp. Stn., Berkeley, Calif.*

Stand condition classification would be a new approach to forest management in the Southwest. Three primary objectives of this system would be to: (1) aid silviculturists in determining the most appropriate silvicultural treatment for each group or stand, (2) provide managers a basis in assigning priorities to accomplish short- and long-term management objectives, and (3) provide foresters with an effective means to communicate among themselves in particular and with conservationists in general. These objectives are not fully met at present.

Purposes for classification.—The purposes for classifying the forest into condition classes are (Hallin 1959):

1. To divide the forest or compartment into natural units sufficiently small and homogeneous for practical, uniform treatments such as harvest cuts, regeneration, and stand improvement.
2. To determine those unit areas which have stands suitable to carry as growing stock, and those which should be harvested to release advanced reproduction or to free ground for new regeneration.
3. To provide the basis for a cutting plan, cutting budget, allowable cut, and other steps in a management plan that will produce healthy stand components of a forest with an acceptable age-class distribution as soon as feasible.

Identification of these stand condition classes should be the manager's first step in the management of a forest. He then has a good grasp of what he has to work with, where it is located, which areas need immediate treatment, what treatments are needed, and which areas can be deferred for future treatment. Without this information, the forest manager is working haphazardly, and his replacement has no idea of what has been done or needs to be done in the future.

A code for condition classes and its application in treatment prescriptions is proposed here. It needs further development before it is ready for use.

Code for condition classes.—Many attributes of a stand or a group of trees could be coded to supply the forest manager with the information he needs to prescribe silvicultural treatments. These attributes could be expressed in a two-digit, two-line code form to describe the overstory (above line) and understory (below line). These attributes may be grouped as: (A) size class and species, (B) stocking density and desirability, (C) damaging agent and severity, and (D) seed tree stocking and

size over ground vegetation and abundance. The various attributes could be coded as:

A. **Size Classes (d.b.h. in inches) (first digit)**

1. 29.0 and over	6. 9.0 – 12.9
2. 25.0 – 28.9	7. 5.0 – 8.9
3. 21.0 – 24.9	8. 0.1 – 4.9
4. 17.0 – 20.9	9. Under 4.5 ft high
5. 13.0 – 16.9	0. None

Species Composition (second digit)

1. Ponderosa pine	6. Douglas-fir, true fir, and pine
2. Spruce	7. Spruce, Douglas-fir, true fir, pine
3. Douglas-fir	8. Spruce, Douglas-fir, true firs
4. True fir	9. Spruce, true fir
5. Aspen	

B. **Stocking Density (ft² basal area per acre) (first digit)**

1. 181 and over	6. 61 – 80
2. 151 – 180	7. 41 – 60
3. 121 – 150	8. 21 – 40
4. 101 – 120	9. 1 – 20
5. 81 – 100	0. <1

Desirability Class (second digit)

1. Areas 70 percent or more stocked with desirable trees.
2. Areas 40-70 percent stocked with desirable trees and having favorable conditions for improved stocking.
3. Areas 40-70 percent stocked with desirable trees and with 30 percent or more of the area controlled by other vegetation, and/or surface condition that prevents occupancy by desirable trees.
4. Areas 10-40 percent stocked with desirable trees but expected to restock naturally.
5. Areas 10-40 percent stocked with desirable trees and requiring planting and/or stand conversion to improve stocking.
6. Areas less than 10 percent stocked with desirable trees but expected to restock naturally.
7. Areas less than 10 percent stocked with desirable trees and requiring planting or artificial seeding.

C. **Damaging Agents** (Indicate most serious causal agent in first digit and severity in second digit as 1 = light, 2 = moderate, and 3 = heavy, except for dwarf mistletoe, use the 6-class severity rating system (Hawksworth and Lusher 1956))

1. Dwarf mistletoe	6. Squirrel
2. Limb rust	7. Tip moth
3. Root rots	8. Cattle or horses
4. Bark beetles	9. Sheep, deer, or elk
5. Porcupine	0. No damage

D. **Seed Trees** (Basal area in seed trees in first digit and their average size class in second digit)

1. 41 – 45	6. 16 – 20
2. 36 – 40	7. 11 – 15
3. 31 – 35	8. 6 – 10
4. 26 – 30	9. 1 – 5
5. 21 – 25	0. <1

Ground Vegetation (List most abundant species as first digit and next most abundant as second digit)

1. Arizona fescue	6. Manzanita
2. Mountain muhly	7. Locust
3. Other grasses	8. Ceanothus
4. Oak brush	9. Weeds
5. Juniper	0. Bare or litter

For example, a ponderosa pine stand with trees over 29 inches in diameter, a stocking density of 200 ft² basal area and no desirable crop trees, heavily infected with dwarf mistletoe, no suitable seed trees, and a ground cover of pine litter would be coded as:

$$\frac{11}{00} = \frac{\text{Overstory of trees 29 inches and over—ponderosa pine}}{\text{No understory}}$$

$$\frac{17}{00} = \frac{\text{Overstory 200 ft}^2\text{ basal area—no desirable trees}}{\text{No understory}}$$

$$\frac{16}{00} = \frac{\text{Heavy infection of dwarf mistletoe in overstory}}{\text{No understory}}$$

$$\frac{00}{00} = \frac{\text{No suitable seed trees}}{\text{Pine litter understory}}$$

The sequence of stand condition attributes would be coded as

$$\left(\frac{11}{00} - \frac{17}{00} - \frac{16}{00} - \frac{00}{00}\right)$$

A two-storied ponderosa pine stand consisting of scattered overstory trees ranging from 25 to 28 inches in diameter, with a basal area stocking of 25 ft^2 all in trees showing a moderate infection of limb rust, and a healthy, well-stocked understory of trees averaging 6 inches in diameter and a stand density of 170 ft^2 per area would be coded as

$$\left(\frac{21}{71}-\frac{87}{21}-\frac{22}{00}-\frac{00}{00}\right)$$

The recognition of condition classes based on the above attributes is not unduly complicated. Although the combination of criteria could theoretically lead to many condition classes, such would not be the case in management units. Most stands would fall within a relatively few condition classes that are repeated throughout the forest.

Application of condition classes for treatment prescriptions.—The condition class description helps lead directly to the appropriate treatment or series of treatments. The immediate objective is to establish or maintain a desirable tree cover, with a long-term objective of organizing the forest property to obtain a continued yield of products and other values. Other information needed might be habitat class and knowledge of stand-site response to possible treatments.

The system of classifying forests by stand condition classes was originally designed for group selection (Hallin 1959), but where units are 1 acre or larger or a series of smaller units can be combined, the shelterwood, seed-tree, or clearcut methods may be appropriate. Therefore, size of the unit area would be considered in prescribing a silvicultural treatment. If the stand described as 11/00-17/00-16/00-00/00 occupied an area up to 1 acre, all trees might be cut and the area regenerated by seed from the adjacent trees, or planted if the trees in the adjacent stand were too young to produce seed. If the stand occupied more than 1 acre, all the trees might be cut and the area planted.

The second stand, described as 21/71-87/21-22/00-00/00, would receive an overstory removal cut and a commercial thinning. Area size would have no bearing on the treatment unless the stand was to be treated with other objectives in mind. The moderate amount of limb rust infection may permit leaving some of the larger trees to provide stand diversity, seed production for wildlife, or nesting places for birds. The understory could also be treated to provide some diversity in tree arrangement for other uses.

Stand Conversion

In the management of our forests, the stand is the essential unit for silvicultural treatment. The stand is defined as a contiguous group of trees, sufficiently uniform in size, species composition, arrangement of age classes, and condition to be a homogeneous, distinguishable, and manageable unit. Ponderosa pine forests consist of many stands, both even-aged and uneven-aged, that vary considerably in area. These stands collectively form the basis for multiple use and sustained yield management of the forest.

Ponderosa pine forest management units have deficiencies or surpluses in certain tree size classes, and great variation in size of individual even-aged and uneven-aged stands. Some of these disparities or characteristics affect decisions on whether to manage for even-aged or uneven-aged stand structures. They also influence the silvicultural treatments chosen to obtain a more balanced size class structure, to improve efficiency of cutting operations, to obtain or maintain nontimber values, and so forth.

Even-aged vs Uneven-aged Stands

Many areas within the southwestern ponderosa pine type can be managed as either even-aged or uneven-aged. If conversion from one to the other is practical and advisable, the conversion should be made without destroying the growing stock. This conversion can be done by combining adjacent groups or stands of similar condition classes, or subdividing large stands into smaller ones. Therefore, conversion may necessitate holding some size class beyond its normal rotation, or stimulating the growth rate of a smaller size class to speed up its entry into the larger size class.

Conversion to Uneven-aged Stands

Pearson (1950) described southwestern ponderosa pine forests as being composed primarily of irregular uneven-aged stands. However, many even-aged stands may be found in a sustained yield unit. These forests are best managed by a combination of even-aged and uneven-aged systems. The stand structure would indicate the form of management.

The manager may want to manage his forest in its entirety as uneven-aged, or specific areas as uneven-aged while others are even-aged to meet multiple use objectives. To convert an even-aged stand to an uneven-aged

stand, the stand is subdivided to create groups of about 2 acres or less in area. In previously unmanaged or extensively managed forests, even-aged stands will have different stand condition classes for which different silvicultural treatments can be prescribed.

Stands of any tree size may be treated to create two or more size classes depending on the stand area. Stands of small and intermediate size trees may be cut to different stocking levels. Trees in the most heavily cut groups would grow more rapidly and advance more quickly into a larger size class, whereas trees in the lightly cut and uncut groups would grow more slowly and remain in the smaller size group. Cuts of intermediate intensity would create other size class groups.

Even-aged stands composed of the larger diameter classes may also be treated to develop into a series of different size class groups. Those portions of the stand with the largest or more defective trees could be cut first to create a new small size class. Other groups may be retained until the next cut or given an intermediate cut to create new size classes. The variation in existing stand conditions would be the basis for silvicultural treatment.

Once uneven ages or sizes have been created in a stand, they can be further differentiated and maintained by the selection method. The time required for conversion would vary by stand condition. Uniform even-aged stands would required a longer period than those with greater diversity.

Conversion to Even-aged Stands

Continued harvest of large saw-log trees may eventually convert many irregular uneven-aged stands to an even-aged structure. Many stands have a light saw-log overstory and a relatively heavy understory of regeneration that started in a few favorable years. Where the understory matrix covers large areas, overstory removal could create an even-aged stand in one cut. Within these stands, open areas wider than the height of the understory trees should be planted. Where the openings are smaller, adjacent trees would hinder establishment of younger trees.

Irregular uneven-aged stands may also be converted to even-aged stands by combining groups that differ by only a few size classes or where the adjacent groups represent the extremes in size classes. Stands with uneven-aged groups that differ only moderately in diameter could be cut to achieve a greater uniformity of size by altering the stand density to change the growth rate. Or these same uneven-aged stands could be thinned to the desired growing stock level and the regeneration cut made when the groups with the smallest trees reach rotation size.

As when converting even-aged to uneven-aged structure, stands should be converted with the least adverse impact on growing stock. The time needed for conversion depends on stand condition; in most stands, however, it may require the remainder of the present rotation period. Subsequent management would be by one of the even-aged methods, with shelterwood as the first choice (Schubert 1973).

Intermediate Cuts

Intermediate cuts include all the cutting treatments made following establishment of the new stand until the time to replace it. Cuttings are made when needed, but normally at specific intervals, to increase the quantity and quality of timber produced, and to salvage material which would be lost. Common intermediate cuts in the Southwest include: (1) thinnings, (2) release cuttings, (3) improvement cuttings, (4) sanitation cuttings, and (5) salvage cuttings. These cuttings apply to all stands regardless of the reproduction method.

Thinnings

Thinnings, either precommercial or commercial, may be made up to the time of the regeneration cut. Early thinnings, which followed the concept of uniform spacing, gave way in 1934 to "crop-tree" thinning, which involved cutting trees within a short radius around the crop tree (Pearson 1940c). Thinning was too light under both of these methods, and failed to produce the desired release.

Since 1962, growing stock levels have been under joint study by the western experiment stations of the USDA Forest Service (Myers 1967). Young even-aged ponderosa pine stands are being studied over a wide range of tree sizes, stand densities, and site qualities. The Taylor Woods plots on the Fort Valley Experimental Forest in north-central Arizona are the only ones in the Southwest.

The treatment in the regionwide study is primarily a low thinning; the smallest trees and rough dominants were removed. The wide range of conditions under investigation should provide data needed to answer questions that arise on quantity and quality of timber products, growth prediction, and application of multiple use management of ponderosa pine forests.

Early results of the Taylor Woods study were reported in the Journal of Forestry (Schubert 1971). These and later results are also summarized in the section on "Growth, Yields, and Quality."

The effect of stand basal area on stem taper and branch diameter will also be evaluated in the growing stock level studies. Early reports have indicated that young southwestern ponderosa pine must be grown in fairly dense stands to obtain low taper and small branches (Pearson 1950). However, earlier studies did not establish what stand density resulted in the best tree form and highest stand volume.

Release Treatments

Release of young trees, below the sapling stage, from the competition of grass, brush, or trees is often necessary to provide adequate growing space, light, and moisture for early rapid development. Young trees competing with dense grass or overtopped by brush and trees are retarded or killed unless they are released, particularly in the dry Southwest (Johnsen et al. 1973).

Timely overstory removal is essential for development of natural reproduction under the shelterwood method. The intense competition for moisture affects growth of both the young stand as well as the overstory trees. Ring counts indicate no significant difference in growth rates of overstory and understory trees.

Herbicides may be used to eliminate grass and brush. Bulldozers and axes may be used to reduce stand density of young seedlings, while power saws are best for removal of larger trees. Poisoning of deformed of wolf trees (Herman 1949, Pearson 1950) has not always been effective or esthetically acceptable. Although many poisoned trees on the Fort Valley Experimental Forest died and eventually disintegrated, others are still alive 40 years after treatment.

Improvement Cuttings

Improvement cuttings, particularly Pearson's "Improvement selection cutting" (Pearson 1942, 1943, 1950), have been effective in Arizona and New Mexico. The primary aim was to build up an effective growing stock. The method involves: (1) removal of trees not expected to live 20 years, (2) removal of low-quality wolf trees and those deformed by lightning, dwarf mistletoe, porcupines, or squirrels, (3) removal of coarse dominants where this will open up groups of yellow pines and blackjacks, (4) regeneration of nonstocked areas, and (5) thinning in groups below saw-log size. In actual practice, the method resembles a sanitation-salvage cutting since items 4 and 5 are seldom done. On the Fort Valley Experimental Forest, the treatment has improved the quality of the residual stand and reduced mortality.

Sanitation and Salvage Cuttings

Salvage cutting was the primary intermediate cut on the National Forests during the first 40 to 50 years of management. The primary objective was to cover the forests as rapidly as possible to reduce heavy losses common in old virgin stands. This objective has generally been fulfilled on most forests.

Sanitation cutting eliminates trees that have been attacked or are likely candidates for attack by insects or disease to prevent the spread of these pests to other trees. Sanitation and salvage cutting are usually combined, and may also be combined with improvement cuttings to improve the stand condition class.

Regeneration Cuttings

The two best regeneration cutting methods for southwestern ponderosa pine are the selection and shelterwood methods. The seed-tree and clearcutting methods are suitable under certain conditions. Because the methods are described in all silviculture textbooks, they will be covered only briefly here, with special reference to the Southwest.

Shelterwood Method

The shelterwood method is designed to produce even-aged stands; it involves removing the entire overstory in one or more cuttings near the end of the rotation. The method can also be used to treat even-aged groups within the group selection method.

The classical three-cut shelterwood includes: (1) a preparatory cut, (2) a seed cut, and (3) a removal cut. The preparatory cut is sometimes omitted.

Even-aged stands of ponderosa pine in the Southwest are managed most effectively by a two-cut shelterwood. The first is a seed cut to establish a stand of seedlings. The second removes the remaining overstory after the seedlings are well established (Schubert 1973). Some stands may require one or more light preparatory cuts, prior to the seed cut, to develop windfirmness and good seed tree

characteristics. Stands most likely to require preparatory cuts are those on sites with shallow soils or high water tables, and where stand density exceeds 200 ft^2 basal area per acre.

The preparatory cut, where needed, removes about 20 to 30 percent of the volume, primarily in trees of lower crown classes and from among the least desirable trees of all crown classes.

The seed cut leaves about 20 to 40 ft^2 of basal area per acre, to provide shelter as well as an adequate seed supply. The seed cut opens up enough growing space for establishment of sufficient reproduction. The trees left should be the best available, preferably about 20 to 24 inches in diameter, and should show evidence of being good seed producers. Beyond the minimum 20 ft^2 of basal area, the stocking left should depend on the need for shelter on the particular site. The seed cut may be made at any time, but the site should be prepared during the fall of a good seed year, and harvesting completed prior to germination the following year.

In the removal cut, all overstory trees should be removed after adequate regeneration is established. This cut should be made while the seedlings are about 1 to 2 ft high and still flexible enough to bend without breaking. Further delay in removing the shelter results in low seedling vigor due to suppression and heavy losses due to breakage. Logs should be removed with the least possible ground disturbance and seedling damage.

Seed-Tree Method

The seed-tree method is designed for even-aged stands of species that produce abundant light seed, and for situations that do not require shelter for seed germination and seedling establishment. It differs from the two-step shelterwood primarily in the number of seed trees retained. In the seed cutting, all trees are removed except for two to four seed trees per acre (Pearson 1923, 1950). The method is not particularly suited for the southwestern ponderosa pine type. It was used successfully during the heavy seed year of 1913 (Pearson 1950), but no other success has been reported.

Clearcutting Method

The clearcutting method is designed for even-aged stands where, for some ecological reason, all trees should be cut. This method has been used sparingly in the southwestern ponderosa pine type in recent years, in stands of 2 to 20 acres where all trees are defective and are unsuitable for seed production.

Clearcutting has been recommended in areas heavily infected with dwarf mistletoe (Andrews 1957, Hawksworth et al. 1968, Korstian and Long 1922, Pearson 1950). Where large areas have been clearcut during a nonseed year, the areas have failed to restock and are now occupied by grass or brush (Pearson 1910, 1950; Pearson and Marsh 1935; Woolsey 1911). Therefore, stands with heavy dwarf mistletoe infection should be carefully examined to determine whether some other regeneration method, such as the shelterwood, could be used. Although dwarf mistletoe reduces cone production (Korstian and Long 1922), extra trees could be retained to make up the needed seed supply. Young seedlings are normally not infected with dwarf mistletoe for up to 10 years.[15] After overstory removal, the young trees could be examined for dwarf mistletoe and all infected trees cut or pruned.

Where clearcutting is used, the area should be planted immediately afterward.

Selection Method

The selection method, designed for uneven-aged stands, is the best way to manage many stands of southwestern ponderosa pine (Schubert 1973). Either single trees or groups may be removed, depending on stand condition and management objectives. Under group selection, the cuttings are most frequently made in groups occupying an area up to 1 acre.

Many of the earlier cuttings by group selection were referred to as "light cuttings" (Pearson 1910). Excellent reproduction followed these light cuttings on the Coconino, Kaibab, Prescott, and Sitgreaves National Forests. Similar results probably were attained on other forests, though not specifically mentioned in the literature or office reports.

A Model for Forest Management

A frequent objective of forest management is to produce the highest possible sustained yield of high-quality trees. This objective can be modified to produce greater volume with reduced quality or higher quality with some reduction of volume. The manager may change the tree size set for final harvest, the growing stock level, management intensity, or any combination of those to accomplish specific objec-

[15] *Personal communication from Frank Hawksworth, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

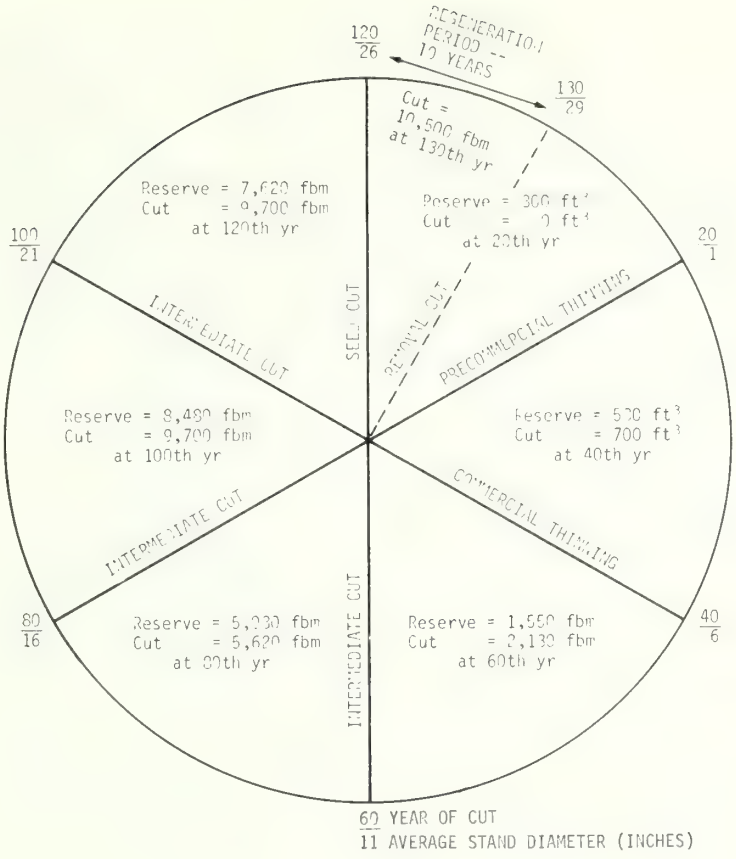

Figure 31.—Schematic diagram for harvesting cutting schedule for management under the shelterwood system at a growing stock level of 60 ft² basal area per acre under a rotation of 120 years and a 20-year reentry period for Site Index 1 land (per-acre basis for volumes).

tives. Within limits, he may convert from one management system to another.

The manager should focus his attention on at least one full rotation, rather than just the segment represented by a 10-year management plan. What he does today was conditioned by past treatments, and will set the stage for the future. He should manage the forest through the application of properly selected and administered silvicultural systems. Under most silvicultural systems, there is sufficient flexibility to revise objectives and adjust prescriptions to meet changing needs.

A schematic diagram (fig. 31) illustrates the series of cuts at 20-year intervals for a 120-year rotation under the shelterwood system for even-aged management. The shelterwood system differs from the seed-tree or clearcutting systems mainly in the way the stand is reproduced. All intermediate cuts would be the same under all three silvicultural systems for even-aged management. Under uneven-aged management by the group selection system, the manager would apply the treatments to even-aged groups in the uneven-aged stands. The scheduled 20-year reentries would be 20-year cutting cycles, and the rotation period would be the time needed to grow the crop to an average of 24 inches in diameter.

A point of primary importance is the retreatment of stands at regular intervals to maintain the desired growth rate. The diagram indicates average stand diameter and yields at 20-year intervals based on an average growth rate of eight rings per inch for a fully stocked stand on a high-quality site. Future research may show that greater yields are possible with shorter reentry intervals or a different growing stock level. The model makes no allowance for mortality. In a well-tended forest, mortality

should be negligible except for rare catastrophic losses (Pearson 1950).

In our example forest, we will start with the seed cut. We will manage each stand at a growing stock level of 60 (GSL-60) ft^2 basal area per acre. At the 120th year (or first year of new rotation) we will have 25 trees averaging 26 inches in diameter with gross volume of 17,320 fbm per acre. We will mark 11 trees per acre to leave for shelter and a seed source for the next crop. These 11 trees (about 40 ft^2 in basal area) will be high quality for timber, shelter, and seed. They must be protected from logging injuries. Our seed cut will remove 14 trees with a gross volume of 9,700 fbm per acre. The soil will be thoroughly scarified during late September in a good seed year.

A regeneration period of 10 years is allowed, based on the average frequency of seed years and time for the new crop of seedlings to become established. Overstory removal will then yield a volume of about 10,500 fbm per acre.

The reproduction stand will average about 1 inch in diameter at the 20th year, at which time we will make a precommercial thinning to GSL-60. This will leave about 500 trees per acre.

Subsequent intermediate cuts, starting with a commercial thinning at age 40, will follow at 20-year intervals with estimated yields and residual tree diameters as indicated in figure 31. Each cut will reduce the stand to GSL-60. The total yield will be about 34,100 fbm per acre for the rotation period, including the overstory removal cut. This total assumes that cuts are made on schedule to maintain the growth rate. Improvement of tree quality will be a major consideration in all intermediate cuts.

Treatment Control

Every silvicultural treatment follows a set of guidelines or prescriptions. These prescriptions are executed in the field by marking the trees and by administering the cutting operation. Both marking and administration are key points in treatment control. Cutting is the main tool in forest management, whether the objective is timber, water, forage, wildlife, recreation, or some combination of these resources. To achieve the stated silvicultural objective, prescriptions are presented as marking rules based on various tree and stand characteristics.

Marking is essential so that the right trees are marked for cutting or leaving to fulfill the treatment objective. Marking rules must be considered as guidelines rather than as rigid rules to be followed blindly. They are intended primarily for the assistance of the forest officer in charge of marking a timber sale. The marker must know the specified silvicultural treatment and have the necessary experience, otherwise the marking rules may not accomplish the stated objective. He should also reexamine the area after cutting to ascertain whether the marking did indeed accomplish the stated objective. Hawley (1946) stated that marking rules, when properly developed, supply the necessary information in concise form and serve as summarized plans of silvicultural management.

Tree Classification

Tree classifications have been used extensively in developing marking rules. Most of the tree classification parameters have been described for individual trees in the selection forest (Dunning 1928). These same characteristics can also be applied to even-aged stands.

The main tree classification factors for timber marking are: age, size, crown position, ground position, vigor, merchantability, potential growth capacity, and mortality. Many of the factors work in concert.

Keen (1943) developed age-vigor classes based on susceptibility to insect attack to guide tree cutting. Under this system, trees are placed in four age classes with four vigor classes. Thomson (1940) found, however, that Keen's age-vigor classes did not fit southwestern ponderosa pine when used as an index of growth for a marking rule. He found that ponderosa pine in the Southwest matured at an earlier age and had smaller average diameters than in California and Oregon. The lowest vigor classes also differed for the Southwest, where they included some larger trees that had once been dominant or codominant. Therefore, Thomson (1940) redefined Keen's age-vigor classes to fit southwestern trees.

Four age classes and five vigor classes were recognized in Thomson's classification. His four age classes (figs. 32, 33) were: (1) young blackjacks mainly under 12 inches d.b.h., (2) blackjacks 12 inches and over, (3) intermediates or young yellow pines (mature), and (4) old yellow pines (overmature). His five vigor classes (figs. 32, 33, 34) were: (1) AA = extremely large crowns with length of 70 percent or more of the total tree height (wolf-type trees); (2) A = full vigor, crowns 55 to 70 percent; (3) B = good to fair vigor, crowns 35 to 55 percent; (4) C = fair to poor vigor, crowns 20 to 25 percent; and (5) D = very poor vigor, crowns less than 20 percent of tree height.

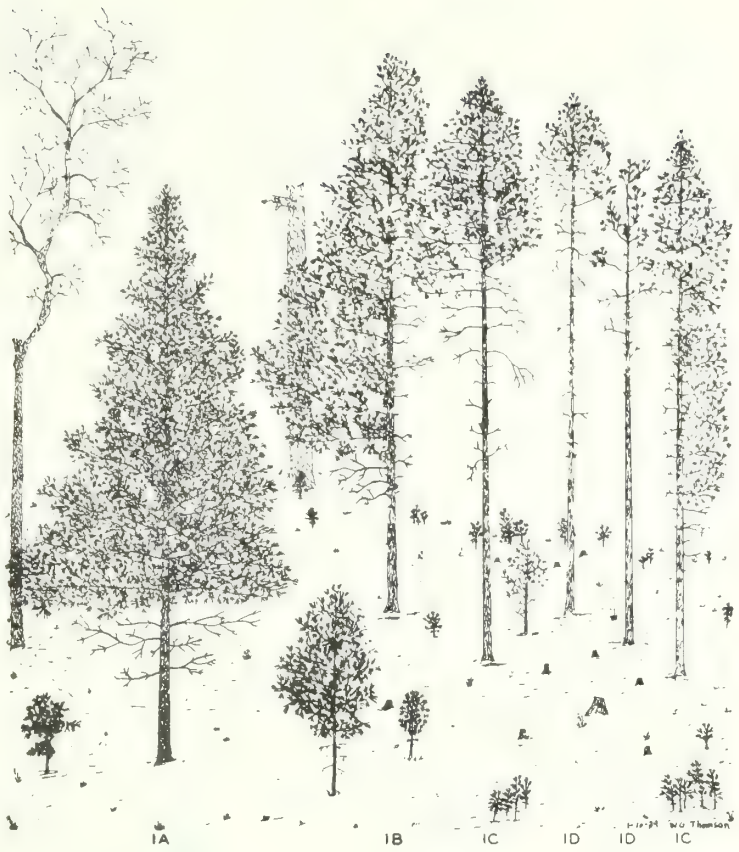

Figure 32.—Age class 1 ponderosa pines. Young blackjacks, usually less than 75 years old and under 12 inches in diameter; growth rates of trees highest for vigor class A and lowest for D (Thomson 1940).

Age-Vigor Marking Rules

When marking is based on age-vigor classes alone, the priority for removal, from highest to lowest, would be: (1) 4D, 3D, 2D, 1D, and all vigor class AA; (2) 4C and 4B; (3) 4A, 3C, and 2C; (4) 3B and 1C; (5) 3A and 2B; (6) 2A and 1B; and (7) 1A.

Other classifications used in marking include the risk rating system (Salman and Bongberg 1942), the Bongberg penalty system for rating high-risk trees (Sowder 1951), and the dwarf mistletoe infection intensity classes (Hawksworth 1961). In the risk rating system, four degrees of susceptibility to bark beetle attack are defined. High risk trees (Risk Class III and IV) should be cut. In the Bongberg penalty system, penalty points are based on needle, twig and branch, and top crown conditions, plus other factors such as vigor classes, lightning strike, beetle attack, and mistletoe. Trees with a penalty score of 9 or more are high risk and should be cut. In the dwarf mistletoe infection rating, 6 classes are set up with zero (no mistletoe), 1 (light mistletoe), and 2 (heavy mistletoe) in each 1/3 of the crown. In a study at the Grand Canyon, 27 percent of the trees with an initial rating of 3 died within 20 years. For trees with a rating of 6, the death rate was 63 percent (Lightle and Hawksworth 1973).

Marking Procedure

Trees should be marked in strips running back and forth over the sale area. The mark should be placed on the back side of the tree so that it is visible to the marker on his return strip. The marker should also indicate the direction of felling where necessary to avoid damage to reproduction and residual trees. Direction of fall can be covered in the sale contract with experienced fallers.

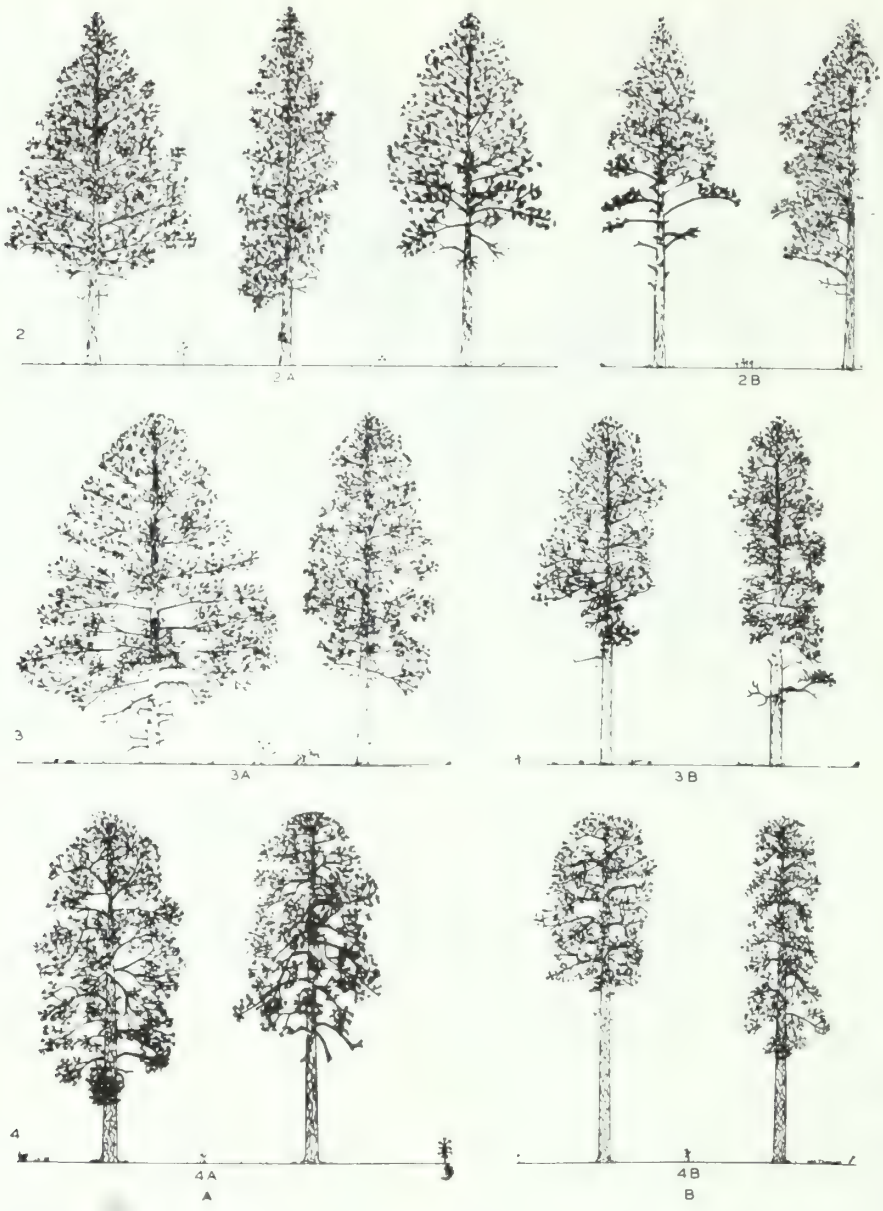

Figure 33.—Age class 2 to 4 ponderosa pines of vigor class A (full) and B (medium). Age class 2 trees are blackjacks, usually less than 150 years and seldom over 24 inches in diameter; age class 3 trees are intermediate-mature, approximately 150 to 225 years old, and usually less than 36 inches. Age class 4 trees are mature-overmature, approximately 225 years old, and usually have large diameter (Thomson 1940).

For the various silvicultural treatments, mark the fewest trees necessary to accomplish the stated objective. For example:

Clearcutting—mark cutting boundary.
Shelterwood—for preparatory cut, mark all trees to be removed. For seed cut, mark all tree to be left. For removal cut, mark boundary.
Seed tree—for seed cut, mark the seed trees For removal cut, mark boundary.
Selection, Intermediate harvest, Improvement and Salvage—mark trees to be cut.

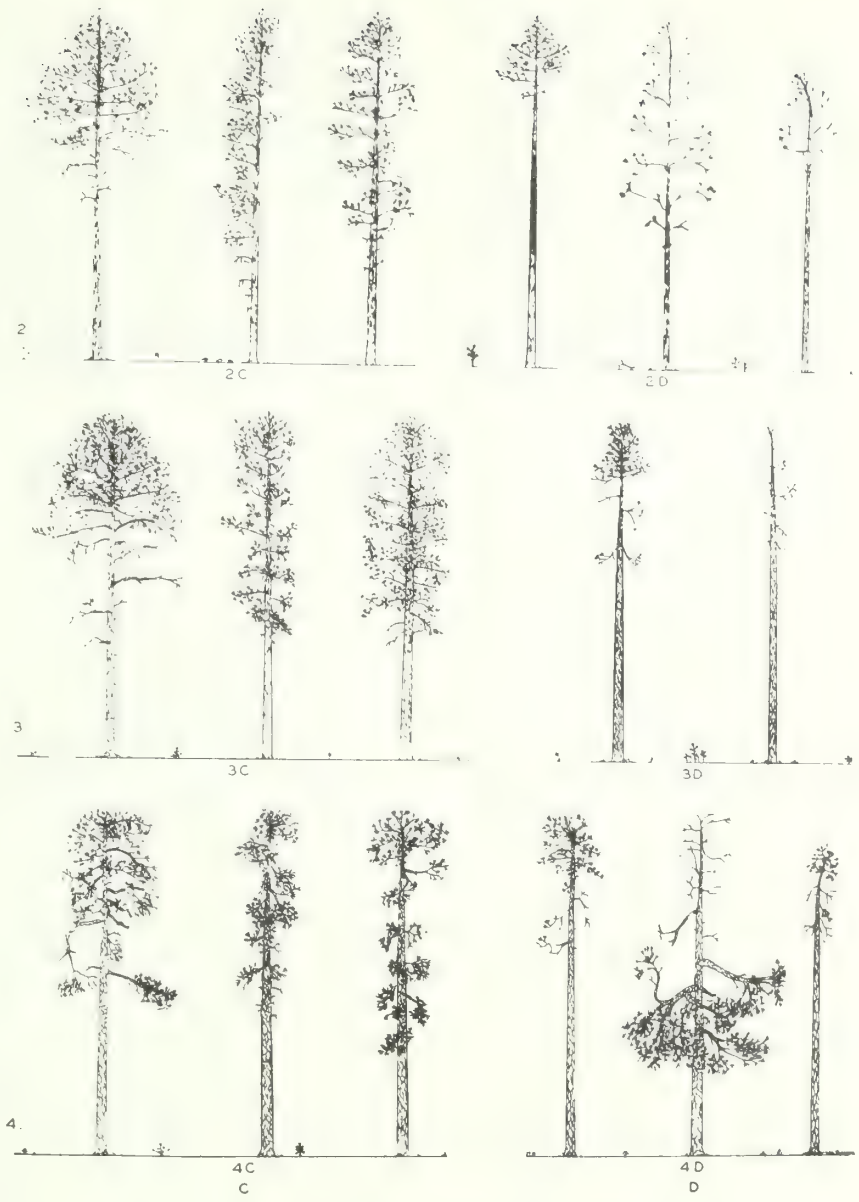

Figure 34.—Age class 2 to 4 ponderosa pines of vigor class C (fair) and D (poor) (Thomson 1940).

Thinning—for precommercial thinning in dense stands use an approximate spacing guide, with instructions on selection of crop trees. For precommercial thinning in less dense stands, and for commercial thinning, mark leave trees.

Multiple-Use Silviculture

Timber management activities in southwestern ponderosa pine have a great impact on all forest values: wood, forage, recreation, water, and wildlife. The standard silvicultural systems discussed will generally provide multiple-use benefits, and commonly can be adapted to emphasize one value or another. For example, by maintaining less basal area and overstory density, and using a shorter cutting interval, both the amount and quality of forage can be increased for wildlife and livestock. Forage production can also be increased by

group selection cutting, and by thinning dense thickets.

In travel and water influence zones, recreation sites, and scenic view areas, individual-tree selection can be used to improve natural beauty. Cutting should be light and the number of trees removed varied throughout the stand to develop diversity. Trees retained should range from seedlings to old, yellow-barked veterans. Natural beauty may also be enhanced by planting hardwood species for their fall coloration.

Forested areas in the ponderosa pine type contribute great amounts of water to meet the critical domestic and agricultural needs in the Southwest. Timber cuttings can be geared to increase water production, influence snow accumulation and rate of melt, and regulate streamflow (Brown 1971). Timber production is rather uniform over a fairly broad range of stand densities. Cutting could maintain these stands at a stocking density to increase water yields without a great decrease in timber yields.

Ponderosa pine stands may also be managed to produce other minor woods products. For example, by maintaining less basal area in pine, Christmas trees could be grown as an understory crop during the latter part of the rotation. Christmas trees could be grown also on landings and spur roads that will be reused at the following reentry for intermediate harvest cuttings.

WHAT WE NEED TO KNOW

Until rather recently, the purposes of forest management in the Southwest were relatively simple: (1) to produce logs for local processing from a forest with abundant standing timber; (2) to utilize available forage; and (3) to maintain a substantial degree of forest cover, or at least vegetative cover, to protect and utilize the land. Esthetic and recreational values were largely incidental.

Increasingly, however, the need is to produce a near-optimum mix of goods and other values. We do not yet know how to do that. It requires identifying the potentials and limitations of each site, considering not only the direct effects of site, but also the effects of existing and alternative vegetation, stand structure and condition, and potential problems of pathology and site damage.

We must understand, in some detail, the processes in the ecosystems now on the sites, and in the ecosystems that may result from proposed treatments. Conversely, we must be able to design prescriptions to accomplish specific results with at least fair precision.

Fortunately, ecosystems that are similar in site and in the composition and structure of their biotic communities behave similarly, and the number of combinations is limited. It is therefore possible to classify sites and communities into a limited number of readily recognizable types within which similar treatments will usually produce similar results.

Within these types we need to know how ponderosa pine and other plants and animals reproduce, grow, and interact with each other and with the physical environment. We need to know with considerable reliability what to expect from a treatment, or absence of treatment, in terms of environmental changes and plant succession.

Among specific questions are: (1) How do different stand densities affect the volume and value of timber production in each ecosystem type? (2) Should growing stock levels (GSL's) be changed when the trees reach different ages or sizes? One aspect of this question is at what age or stocking level should a stand first be thinned. (3) How frequently should stands be treated? Twenty-year intervals have been used in examples here, but the best intervals may vary by site, GSL, and so forth.

It is important that field and computer simulation procedures for predicting growth and yield be tied to habitat types, and be expanded to include uneven-aged stands and key uses besides timber production.

Can the timber quality or growth of southwestern ponderosa pine be increased through provenance selection, genetic improvement programs, or fertilization?

Evaluation of fire is needed. How much can prescribed burning reduce disastrous wildfires? What are its side effects? Its multiple use impacts?

Available artificial reforestation methods are reasonably reliable if carried out correctly. Natural regeneration methods, though commonly much cheaper, are unreliable. The general requirements for successful natural regeneration are known, but the factors that are critical in different habitat types must be identified and reliable methods developed. A critical need is to determine suitable stand densities and necessary site preparation in the shelterwood method, and suitable sizes for openings in the group selection method, for different habitat types and stand conditions.

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APPENDIX

COMMON AND SCIENTIFIC NAMES OF PLANTS, ANIMALS, DISEASES, AND INSECTS ASSOCIATED WITH SOUTHWESTERN PONDEROSA PINE

Common Name	Scientific Name
Large and Medium-Sized Trees	
Aspen, quaking	*Populus tremuloides* Michx.
Boxelder, inland	*Acer negundo* var. *interius* (Britton) Sarg.
Douglas-fir, Rocky Mountain	*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco
Fir, white	*Abies concolor* (Gord. and Glend.) Lindl.
Juniper, alligator	*Juniperus deppeana* Steud.
Juniper, Rocky Mountain	*J. scopulorum* Sarg.
Maple, bigtooth	*Acer grandidentatum* Nutt.
Oak, Gambel	*Quercus gambelii* Nutt.
Pine, Apache	*Pinus engelmannii* Carr.
Pine, Arizona	*P. ponderosa* var. *arizonica* (Engelm.) Shaw
Pine, Chihuahua	*P. leiphylla* var. *chihuahuana* (Engelm.) Shaw
Pine, limber	*P. flexilis* James
Pine, ponderosa	*P. ponderosa* Laws.
Pine, southwestern white	*P. strobiformis* Engelm.
Walnut, Arizona	*Juglans major* (Torr.) Heller
Small Trees and Shrubs	
Bitterbrush, antelope	*Purshia tridentata* (Pursh) DC.
Buckthorns	*Rhamnus* spp.
Ceanothus, Fendler	*Ceanothus fendleri* A. Gray
Cherry, bitter	*Prunus emarginata* (Dougl.) D. Dietr.
Chokecherry, common	*P. virginiana* L.
Cliffrose	*Cowania mexicana* D. Don
Currant, wax	*Ribes cereum* Dougl.
Deerbrush	*Ceanothus integerrimus* Hook. & Arn.
Dogwood, red-osier	*Cornus stolonifera* Michx.
Elder, blueberry	*Sambucus glauca* Nutt.
Gooseberry, orange	*Ribes pinetorum* Greene
Juniper, common	*Juniperus communis* L.
Juniper, one-seed	*J. monosperma* (Engelm.) Sarg.
Juniper, Utah	*J. osteosperma* (Torr.) Little
Locust, New-Mexican	*Robinia neomexicana* A. Gray
Manzanita	*Arctostaphylos* spp.
Mountainmahogany, curlleaf	*Cercocarpus ledifolius* Nutt.
Ninebark, mountain	*Physocarpus monogynus* (Torr.) Coult.
Oak, shrub live	*Quercus turbinella* Greene
Pinyon	*Pinus edulis* Engelm.
Poison-ivy, western	*Toxicodendron radicans* var. *rydbergii* (Small) Rehder
Rabbitbrushes	*Chrysothamnus* spp.
Raspberry, American red	*Rubus strigosus* Michx.
Roses	*Rosa* spp.
Serviceberry, Utah	*Amelanchier utahensis* Koehne
Snowberry	*Symphoricarpos oreophilus* A. Gray
Sumacs	*Rhus* spp.
Thimbleberry, western	*Rubus parviflorus* Nutt.
Willows	*Salix* spp.

Common Name	Scientific Name
Forbs, Grasses, and Grasslike Plants	
Bluegrasses	*Poa* spp.
Bluestem, little	*Andropogon scoparius* Michx.
Bracken	*Pteridium aquilinum* (L.) Kuhn
Bromes	*Bromus* spp.
Cheatgrass	*Bromus tectorum* L.
Dropseed, black	*Sporobolus interruptus* Vasey
Dropseed, pine	*Blepharoneuron tricholepis* (Torr.) Nash
Fescue, Arizona	*Festuca arizonica* Vasey
Fescue, Idaho	*F. idahoensis* Elmer
Grama, blue	*Bouteloua gracilis* (H.B.K.) Lag.
Groundsel, broom	*Senecio spartioides* Torr. & Gray
Irises	*Iris* spp.
Johnsongrass	*Sorghum halepense* (L.) Pers.
Junegrasses	*Koeleria* spp.
Larkspurs	*Delphinium* spp.
Lupines	*Lupinus* spp.
Milkweeds	*Asclepias* spp.
Muhly, mountain	*Muhlenbergia montana* (Nutt.) Hitchc.
Muhly, ring	*M. torreyi* (Kunth) Hitchc.
Muhly, spike	*M. wrightii* Vasey
Mullein, purple-stamen	*Verbascum virgatum* Stokes
Needlegrasses	*Stipa* spp.
Orchardgrass	*Dactylis glomerata* L.
Redtop	*Agrostis alba* L.
Ryegrass, perennial	*Lolium perenne* L.
Squirreltail, bottlebrush	*Sitanion hystrix* (Nutt.) J.G. Smith
Sunflower, common	*Helianthus annuus* L.
Thistles	*Cirsium* spp.
Three-awns	*Aristida* spp.
Wheatgrasses	*Agropyron* spp.
Yarrow, western	*Achillea lanulosa* Nutt.
Mammals	
Chipmunks	*Eutamias* spp.
Cottontails	*Sylvilagus* spp.
Coyote	*Canis latrans* Say
Deer, mule	*Odocoileus hemionus hemionus* Rafinesque
Deer, white-tailed	*O. virginianus* (Zimmermann)
Elk, Rocky Mountain	*Cervus elaphus* (Linneaus)
Ground squirrel, golden-mantled	*Spermophilus lateralis* (Say)
Ground squirrel, spotted	*S. spilosoma* Bennett
Jack rabbit, black-tailed	*Lepus californicus* Gray
Myotises	*Myotis* spp.
Pocket gophers	*Thomomys* spp.
Porcupine	*Erethizon dorsatum* (Linnaeus)
Prairie dog, Gunnison's	*Cynomys gunnisoni* (Baird)
Pronghorn	*Antilocapra americana* Ord
Shrew	*Sorex* spp.
Skunk	*Mephitis* spp.
Squirrel, Abert's	*Sciurus aberti* Woodhouse

Common Name	Scientific Name
Squirrel, Arizona gray	*S. arizonensis* Coues
Squirrel, Kaibab	*S. kaibabensis* Merriam
Squirrel, red	*Tamiasciurus hudsonicus* (Erxleben)
Voles	*Microtus* spp.
Woodrats	*Neotoma* spp.

Birds

Chickadee, mountain	*Parus gambeli* Ridgway
Crow, common	*Corvus brachyrhynchos* Brehm
Dove, mourning	*Zenaida macroura* Linneaus
Flicker, common	*Colaptes auratus* (Linnaeus)
Grosbeak, black-headed	*Pheucticus melanocephalus* Swainson
Grosbeak, evening	*Hesperiphona vespertina* Cooper
Jay, pinon	*Gymnorhinus cyanocephalus* Wied
Jay, Steller's	*Cyanocitta stelleri* Gmelin
Juncos	*Junco* spp.
Nutcracker, Clark's	*Nucifraga columbiana* Wilson
Nuthatches	*Sitta* spp.
Pigeon, band-tailed	*Columba fasciata* Say
Raven, American	*Corvus corax* Linnaeus
Robin	*Turdus migratorius* Linnaeus
Sapsuckers	*Sphyrapicus* spp.
Starling	*Sturnus vulgaris* Linnaeus
Turkey, Merriam's	*Meleagris gallopavo merriami* Nelson
Woodpecker, acorn	*Melanerpes formicivorus* Swainson
Woodpecker, downy	*Dendrocopos pubescens* Linnaeus
Wookpecker, hairy	*D. villosus* Linnaeus
Woodpecker, Lewis	*Asyndesmus lewis* Gray

Diseases

Seedling diseases

Fusarium damping-off	*Fusarium* spp.
Pythium damping-off	*Pythium* spp.
Rhizina root rot	*Rhizina undulata* Fr.
Rhizoctonia damping-off	*Rhizoctonia solani* Kuehn
Sclerotium damping-off	*Sclerotium bataticola* Taub.

Stem diseases

Dwarf mistletoe	*Arceuthobium vaginatum* subsp. *cryptopodum* (Engelm.) Hawks. & Wiens
Atropellis canker	*Atropellis arizonica* Lohm. & Cash
Pine canker	*A. piniphila* (Weir) Lohm. & Cash
Comandra rust	*Cronartium comandrae* Pk.
Limb rust	*Peridermium filamentosum* Pk.
Western gall rust	*P. harknessii* J.P. Moore

Needle diseases

Dothistroma needle blight	*Dothistroma pini* Hulb.
Elytroderma needle blight	*Elytroderma deformans* (Weir) Dark.
Hypodermella needle blight	*Davisomycella medusa* (Dear.) Dark.
Prescott needle cast	*Lophodermella cerina* (Dark.) Dark.

Common Name	Scientific Name
Root rots	
Armillaria root rot	*Armillaria mellea* Vahl.
Fomes root rot	*Fomes annosus* (Fr.) Cke.
Stem rots	
Brown trunk rot	*Fomes officinalis* (Vill. ex Fr.) Faull
Red ring rot	*F. pini* (Thore) Lloyd
Western red rot	*Polyporus anceps* Pk.
Red-brown butt rot	*P. schweinitzii* Fr.

Insects

Cone and seed insects	
Pine cone beetle	*Conophthorus scopulorum* Hopk.
Fir coneworm	*Dioryctria abietella* D. & S.
Pine coneworm	*D. auranticella* Grote
Pine seed moth	*Laspeyresia piperana* Kearf.
Root feeders	
White grubs	*Phyllophaga* spp.
Wireworms	Elateridae
Cutworms	Noctudae
Bark beetles	
Colorado pine beetle	*Dendroctonus parallelocollis* Chap.
Mountain pine beetle	*D. ponderosae* Hopk.
Red turpentine beetle	*D. valens* Lec.
Roundheaded pine beetle	*D. adjunctus* Bland.
Southern pine beetle	*D. frontalis* Zimm.
Western pine beetle	*D. brevicomis* Lec.
Arizona five-spine ips	*Ips lecontei* Sw.
California pine engraver	*I. plastographus* Lec.
No common name; locally known as Cloudcroft ips	*I. cribicollis* (Eichh.)
Knaus ips	*Ips knausi* Sw.
Pine engraver	*Ips pini* Say
Butterfly, moths, and scale	
Pine butterfly	*Neophasia menapia* Feld.
Pine shoot moth	*Eucosma sonomana* Kearf.
Ponderosa twig moth	*Dioryctria ponderosae* Dyar.
Ponderosa pine sawfly	*Neodiprion fulviceps* Cress.
Colorado pine sawfly	*Neodiprion gillettei* Roh.
Pine tiger moth	*Halisidota ingens* Hy. Edws.
Southwestern pine tip moth	*Rhyacionia neomexicana* (Dyar)
Prescott scale	*Matsucoccus vexillorum* Morrison

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Abstract

Schubert, Gilbert H.
1974. Silviculture of southwestern ponderosa pine: The status of our knowledge. USDA For. Serv. Res. Pap. RM-123, 71 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Describes the status of our knowledge of ponderosa pine silviculture in the southwestern States of Arizona, Colorado, New Mexico, and Utah. Economic value, impact on other uses, and the timber resource are discussed first, followed by ecological background, site quality, growth and yield, and silviculture and management. Relevant literature is discussed along with observations, experience, and results of unpublished research. Treatise is intended to serve as a reference tool for guidance in making management decisions and prescribing silvicultural treatments. Research needs are also considered.

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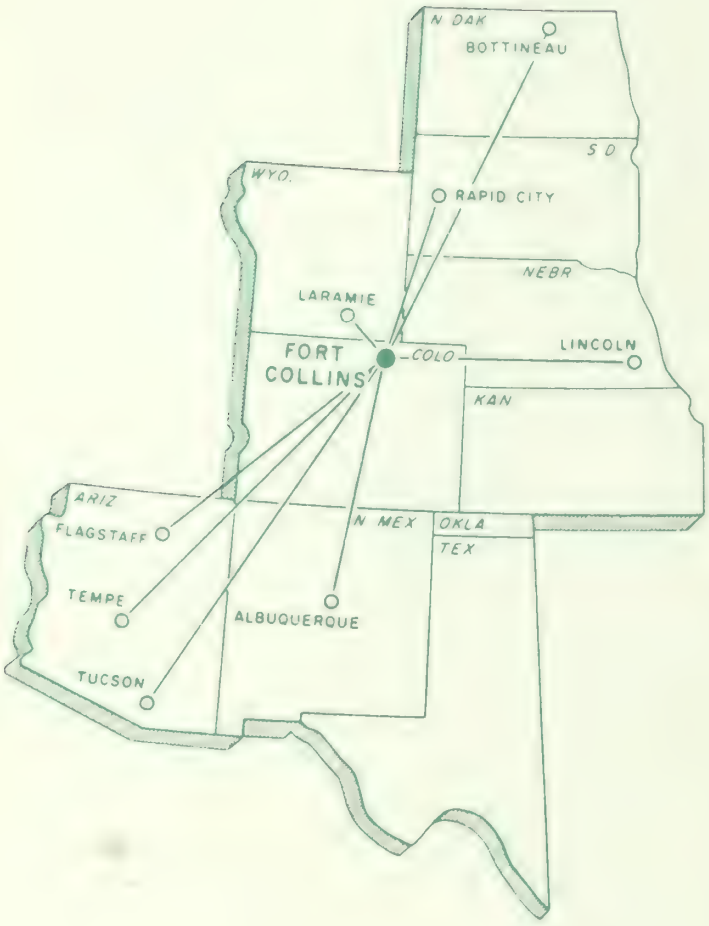
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SILVICULTURE OF PONDEROSA PINE IN THE BLACK HILLS: The Status of Our Knowledge

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ABSTRACT

This Paper, intended as a guide for professional foresters, describes major silvicultural conditions likely to be encountered in the Black Hills, reasonable treatment options, and probable results and implications of these treatments. It also describes silvical characteristics and behavior of Black Hills ponderosa pine, and a variety of proven silvicultural tools.

Oxford: 181$174:187. **Keywords:** Timber management, silviculture systems, Black Hills ecology, *Pinus ponderosa*.

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USDA Forest Service
Research Paper RM-124

June 1974

SILVICULTURE OF PONDEROSA PINE IN THE BLACK HILLS: The Status of Our Knowledge

by

Charles E. Boldt, Silviculturist

and

James L. Van Deusen, Associate Silviculturist

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University; authors are located at the Station's Research Work Unit at Rapid City, in cooperation with the South Dakota School of Mines ano Technology.*

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SILVICULTURE OF PONDEROSA PINE IN THE BLACK HILLS: The Status of Our Knowledge

Charles E. Boldt and James L. Van Deusen

INTRODUCTION

BLACK HILLS FORESTS: A MODEL OF SUSTAINED YIELD

The ponderosa pine (*Pinus ponderosa*) of the Black Hills cannot be expected to match the high levels of wood production attained by forests in areas which are favored by more abundant precipitation, deeper and richer soils, and longer growing seasons. But, while the rigors of the Black Hills environment do impose fairly stringent limitations on forest growth and yield potentials, the fact remains that the area is intrinsically well suited to timber crop culture. This basic premise is neither speculative nor theoretical—its validity has been demonstrated by actual forest responses to nearly a century of consumptive use.

During this period, virtually all of the area's unreserved and operable forest acres have been cut over at least once; many acres have received multiple partial cuts. Large tracts which were logged free of regulatory restraints—prior to establishment of the Forest Reserve in 1897—were commercially clearcut and practically stripped of all trees large enough to yield a mine timber or a railroad tie.

Persistent harvesting, coupled with the destructive impacts of wildfire, insects, diseases, and wind, have nearly eliminated the original old-growth sawtimber stands on upwards of one-half of the commercial forest acres in the Black Hills, and left only light stands of scattered old-growth remnants on the bulk of the remaining acreage.

Despite these massive withdrawals, however, growing stock capital has not been depleted. On the contrary, it has increased steadily in recent decades to unprecedented levels. Total annual increment of merchantable wood, forestwide, has also increased until it is now roughly equal to the average annual cut during the 21 years of unhampered forest exploitation which preceded establishment of the Reserve (USDA-USDI 1967). It is equally remarkable, after all this harvest activity, that only about 1 percent of the commercial forest acres in the Black Hills are currently classed as inadequately stocked for timber production.

The important implication of these facts seems clear: the old-growth pine forest of the Black Hills has been converted—with uncommon success and completeness—to a well-stocked and manageable second-growth forest. Furthermore, the conversion has been accomplished with no large or prolonged falldown in forest productivity. These facts provide convincing evidence of the feasibility of successful timber crop culture in Black Hills ponderosa pine, on a sustained basis. All that is needed is sufficient managerial skill and silvicultural know-how.

PURPOSE OF PAPER

This Paper is an attempt to bring together in a single reference most of what is known about silviculture of ponderosa pine in the Black Hills. The Paper is intended specifically as a field guide for professional foresters who are responsible for prescribing and supervising the application of silvicultural treatments in the woods. It attempts to describe (1) all of the major silvicultural conditions, or problem situations, that the field practitioner is likely to encounter, (2) the treatment options that reasonably may be exercised in each particular situation, and (3) the probable results and practical implications of the various options—insofar as they are predictable—to help the silviculturist choose the option which will come closest to satisfying established management

goals. The Paper also contains relevant background information on silvical characteristics and behavior of ponderosa pine in the Black Hills environment, along with an assortment of working tools that have proven helpful in doing a variety of silvicultural jobs.

Much has been learned about the culture of ponderosa pine crops in the Black Hills since Case Number 1 marked the beginning of forest husbandry in the area in 1898.[2] The existing fund of information has been generated by both experience and research. Inevitably, some of what has been learned has never been adequately documented, and that which has been recorded is scattered through a variety of information sources—published and unpublished, old and new. Consequently, a concerted effort and considerable digging is required to piece together a reasonably complete composite picture of the state of silvicultural knowledge and know-how in the Black Hills. Unfortunately, most of the foresters who are actually guiding the practice of silviculture have neither the time nor the resources to tackle this fairly formidable exercise in information retrieval. This Paper has been written for them.

[2]*Case Number 1 was a landmark in American forestry in that it was the first exercise of the provisions of the Organic Act of 1897, the first sale of Federally-owned timber, and the first instance of regulated timber harvest on the newly created Forest Reserves (Jackson 1951).*

SILVICS

HABITAT

The Black Hills and Bear Lodge Mountains were formed by a regional uplift of the earth's surface millions of years ago. About two-thirds of this elliptically shaped, maturely dissected, domal structure lies in South Dakota; the other third, including all of the Bear Lodge Mountains, is in Wyoming (fig. 1).

Because of similarities in geologic makeup and responses to erosion, both the Black Hills and Bear Lodge Mountains have developed the same four visible and distinctive gross geomorphologic features: (1) a "hogback ridge" of mesozoic sandstone, limestone, and shale, more or less continuous and encircling the whole area; (2) a "red valley," least developed on the east side, and made up of less resistant sedimentary formations, containing some gypsum and iron deposits (which give the soil its characteristic color); (3) a limestone plateau composed of remnants of a once-continuous cap of deep

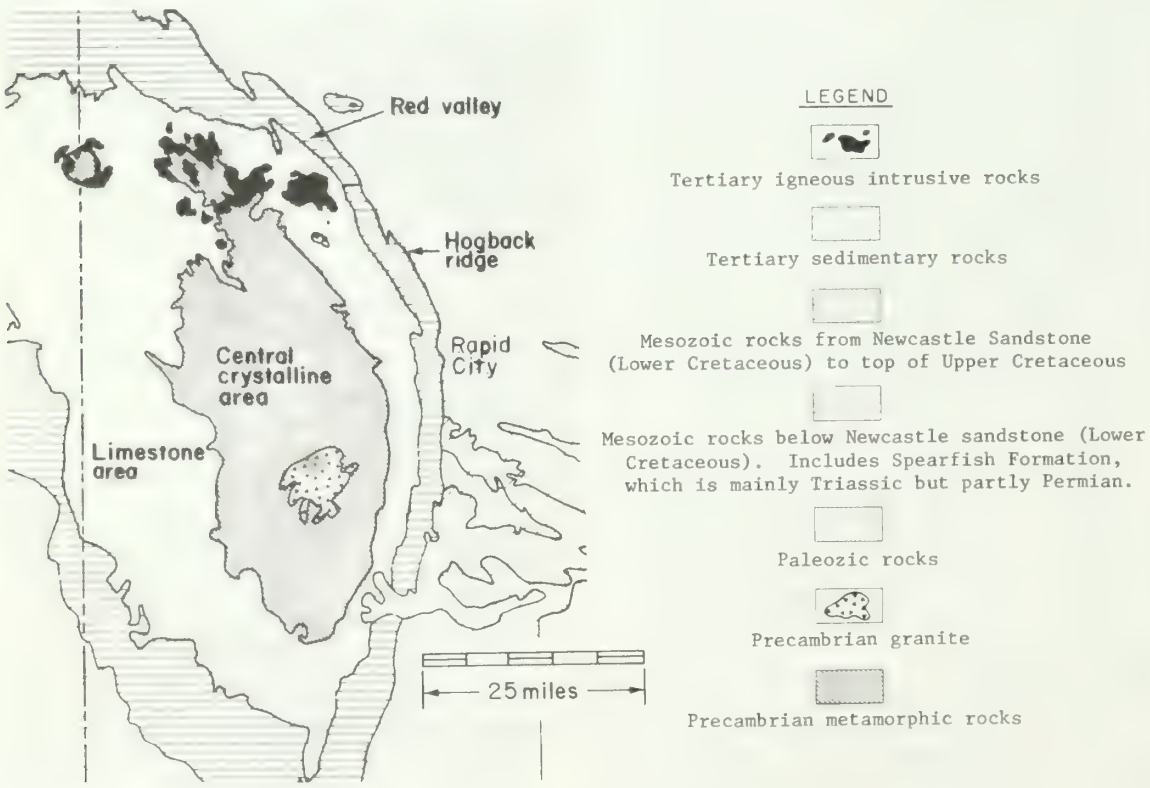
Red valley
Hogback ridge
Rapid City
Central crystalline area
Limestone area
25 miles
LEGEND
Tertiary igneous intrusive rocks
Tertiary sedimentary rocks
Mesozoic rocks from Newcastle Sandstone (Lower Cretaceous) to top of Upper Cretaceous
Mesozoic rocks below Newcastle sandstone (Lower Cretaceous). Includes Spearfish Formation, which is mainly Triassic but partly Permian.
Paleozic rocks
Precambrian granite
Precambrian metamorphic rocks

Figure 1.—Generalized geologic map of the Black Hills.

sedimentary layers of paleozoic age; and (4) a central core of crystalline rocks consisting of intruded, igneous material and surrounding metasediments. The first three of these four geologic features encircle the crystalline core in concentric bands of varying width (fig. 2), each with its own distinctive geomorphic characteristics. The entire system is elevated 1,000 to 4,000 ft above the surrounding plains.

The central, crystalline area is characterized by rough to rounded hills and divides with elevations which generally range from 4,300 to 6,000 ft. Two of the highest peaks in this area, Harney and Terry, both exposed igneous intrusions, rise to 7,242 and 7,077 ft, respectively.

On the eastern side of the Black Hills, the limestone plateau forms a narrow ridge occasionally flattening out to narrow uplands with elevations of 3,600 to 4,400 ft. However, the plateau is much more extensive on the west than on the east side because of generally lower west-side dips. Here, the deep sedimentary

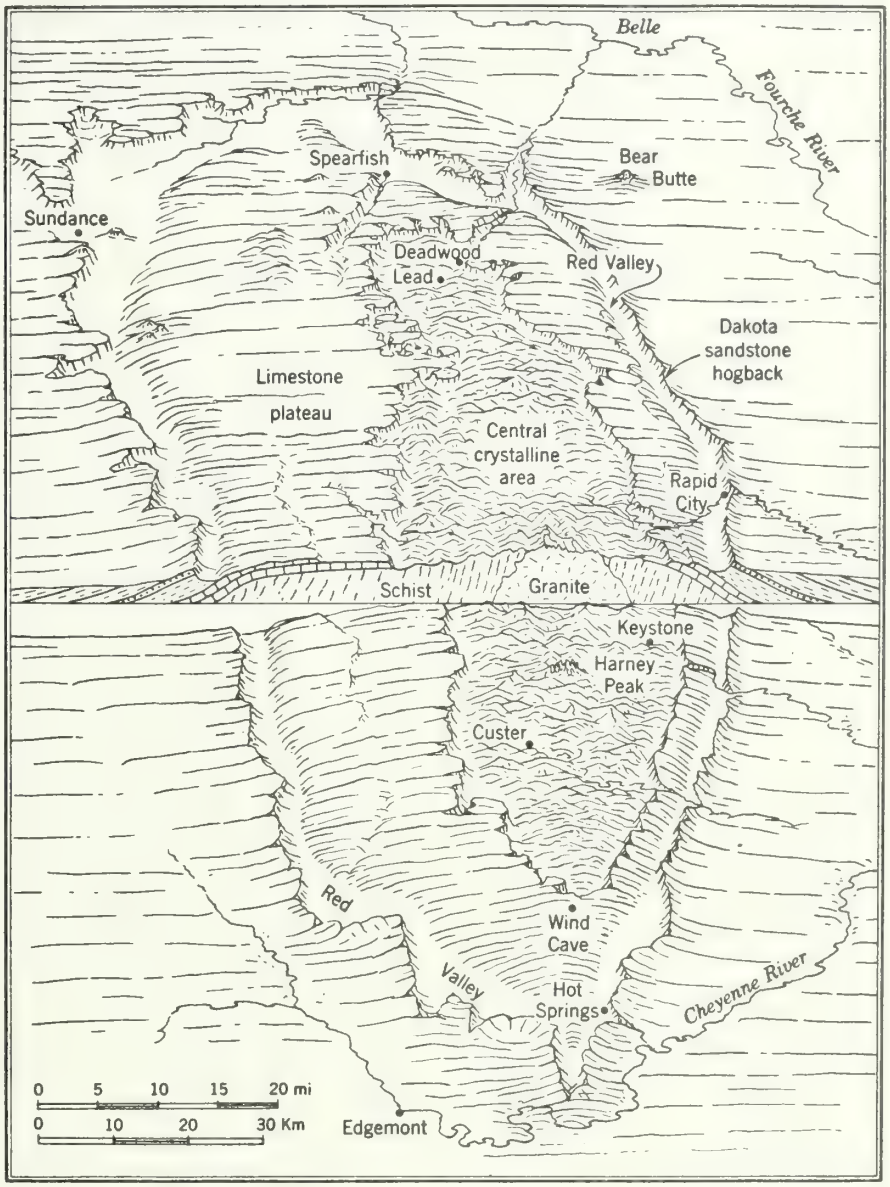

Figure 2.—Diagram of Black Hills showing the main topographic regions on this broad domal structure. (From Strahler, Physical Geography, 3d ed., copyrighted 1969 by John Wiley & Sons, Inc., N.Y. Reproduced by permission.)

formations form wide, rather level divides separated by narrow, steep valleys. Elevations range from 4,500 to slightly over 7,000 ft.

Of the four major landform features, the central crystalline area and the limestone plateau are the main timber-producing areas. In addition, the really important discharges occur in watersheds of the same areas. Limitations imposed by precipitation, soils, areal extent, and mounting competition by other land uses in the red valley and hogback sectors restrict the potentials of these areas for successful forest culture for wood production.

Soils in the Black Hills have not been surveyed, but their general profile characteristics approximate those of the Gray Wooded Soils Group. Radeke and Westin (1963), who examined about 30 profiles during their investigation, described the wooded soils of the Black Hills as having the following general profile characteristics:

01	F layer, 1-2 inches thick	Forest litter, partially decomposed.
02	H layer, 1-2 inches thick	Decomposed forest litter.
A2	Horizon, 3-15 inches thick	Gray loam or silt loam; weak platy structure; very friable moist.
A2 and B2t	Horizon, 2-9 inches thick	A transition zone of variable depth and thickness. Brown loam to silty clay loam; moderate fine blocky structure; blocks often coated with gray dust; friable moist.
B2t	Horizon, 5-26 inches thick	Brown clay loam to clay; moderate to strong blocky structure; very firm moist.

These morphological characteristics generally agree with those found by Myers and Van Deusen (1960) in the more than 100 profiles they examined throughout the Black Hills and Bear Lodge Mountains. Soil depths, measured to the top of the C horizon, ranged from 2 to 57 inches, with an average of 24 inches.

The climate of the Black Hills and Bear Lodge Mountains is modified from that of the surrounding plains by the prominence of the uplift itself, which gives rise to an orographic rainfall belt. Precipitation is increased, while temperature extremes are reduced.

Average annual precipitation ranges from 17 inches in the southern Hills to a small zone of more than 28 inches near Lead in the northern Black Hills. Annual precipitation in the Bear Lodge Mountains averages 18 to 24 inches (fig. 3). Sixty to seventy percent of the annual precipitation falls from April to September. May and June are normally the wettest months; January and February are usually the driest (Orr 1959).

Length of growing season in the region averages about 100 days. Average monthly air temperatures vary from about 68° F in July to 22° F in December, while average annual air temperatures range from 41° to 45° F.

Though pure stands of ponderosa pine are usual, white spruce (*Picea glauca* var. *densata*) occupies about 2 percent of the commercial forest acres and accounts for about 4 percent of the total timber volume. Spruce often grows in nearly pure stands, along stream channels, lower slopes, and north-facing slopes of the northern Black Hills. Oddly, spruce is not found in the Bear Lodge Mountains.

Lodgepole pine (*Pinus contorta*) is also apparently native to the Black Hills, but is found as isolated trees, or in a more or less pure stand of 125 acres north of Rochford. Only isolated trees of lodgepole pine have been found in the Bear Lodge Mountains.

Several other tree species are native to the area, growing in association with ponderosa pine. They represent the montane forests to the west as well as northern and eastern boreal forests. Most abundant are quaking aspen (*Populus tremuloides*), paper or white birch (*Betula papyrifera*), bur oak (*Quercus macrocarpa*), and Rocky Mountain juniper (*Juniperus scopulorum*). A single, small stand of limber pine (*Pinus flexilis*) in the Harney Peak area has been described by Thilenius (1970).

SPECIES BEHAVIOR

Ponderosa pine is a dependable seed producer in this region. Seed crops are normally good to excellent, by local standards, every 2 to 5 years; the longtime average interval between good crops is 3 years.[3] This characteristic, coupled with favorable spring and summer moisture conditions, makes natural reproduction readily and abundantly available. Ordinarily, it is only where a suitable seed source is absent that one must resort to seeding or planting to restock deforested sites.

Extremely high stand densities are common in naturally regenerated stands (fig. 4). Dense seedling stands often contain more than one

[3] *In some years, perhaps, cones and seed will be produced in abundance throughout the area. More typically, though, crops will show considerable local variation in any given year. Widespread crop failures are probably more common than widespread bumper crops.*

tree per ft². Unfortunately, natural thinning normally proceeds very slowly, so that initially crowded stands are apt to remain overstocked for long periods, perhaps their full lifespan. For example, a plot stand adjacent to the one shown in figure 4 contained 15,000 trees per acre at age 12. At age 63, it still contained 6,600 trees per acre, with an average d.b.h. of

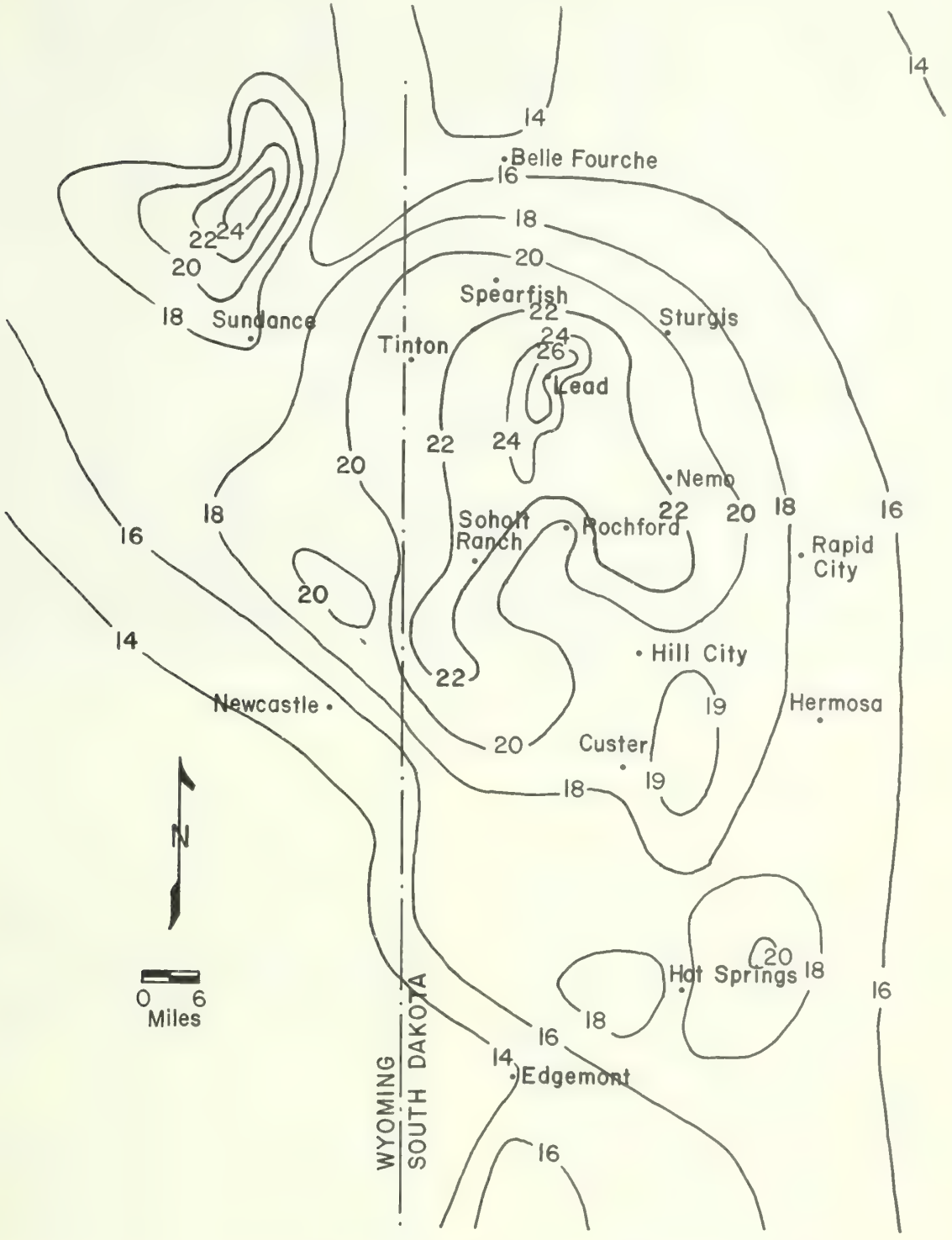

Figure 3.—Isohyetal map of average annual precipitation in the Black Hills area (Orr 1959).

Figure 4.—Stagnant sapling stand: 63 years old; 5,800 trees per acre; average d.b.h., 2.5 inches.

only 2.4 inches (Myers and Van Deusen 1960a).

Though stands may become and remain so dense that they stagnate, release by thinning can produce striking growth responses at most any age.

There is ample evidence that good silviculture can enhance productivity of Black Hills pine sites and stands. However, one must keep in mind that species behavior is strongly influenced by certain environmental factors which impose upper limits on the productivity potentials of Black Hills forest land: (1) a relatively short growing season; (2) limited precipitation; (3) frequent high temperatures, persistent winds, and low humidity during the growing season, all increasing evapotranspiration; and (4) a generally shallow soil mantle with limited capacity for moisture storage.

DAMAGING AGENTS

There are a variety of agents that kill or deform ponderosa pine trees and stands in the Black Hills. Some pose a continual threat, while the impact of others tends to be greatest at some particular stage of tree or stand development.

INSECTS

Only one native insect has demonstrated a capacity for devastating Black Hills pine forests—the mountain pine beetle (*Dendroctonus ponderosae* Hopk.). At epidemic levels, this pest has killed entire stands of pine, greatly influencing the distribution of age classes throughout the area.

Three other insects are of varying but lesser importance throughout the Hills: the pine engraver (*Ips pini* Say); red turpentine beetle (*Dendroctonus valens* LeConte); and pine tip moths (*Rhyacionia* spp.).

Mountain Pine Beetle

General Description

The mountain pine beetle, formerly known in this area as the Black Hills beetle, has been a serious economic pest as long as records have been kept of its activity. An extremely serious outbreak swept through the area between 1895 and 1910, killing trees that contained an estimated 1 to 2 billion fbm (board feet) of lumber. More recently, the northern Hills has been the scene of two serious buildups. In 1963, severe and widespread losses were averted by concentrated efforts of Federal, State, and contract insect control crews. Another outbreak is currently underway. During these increases to destructive levels, annual pine mortality may exceed 50,000 trees.

McCambridge and Trostle (1972) and Cole and Shepherd (1967) present complete yet concise descriptions of the life history and damage caused by the mountain pine beetle. Attacks are usually manifested by reddish- to yellowish-brown "pitch tubes" on the bole from ground to midcrown (fig. 5). Sometimes a copious flow of resin from the tree will prevent successful attack by the beetle. These unsuccessful attacks are called "pitchouts."

The only early external sign of a successful attack is sawdust in the bark crevices or on the ground at the base of the tree. A few weeks after attack, bluestaining fungi, carried into the trees by the beetles, discolor the sapwood. This is a second, and certain indication that the tree has been successfully attacked and killed. The fungi appear to be essential to successful attacks and brood establishment.

Foliage discoloration, known as "fading," provides later evidence of infestation. Chlorophyll loss can start within 3 to 4 weeks after attack, but it usually is not noticeable until the following spring. The needles eventually become a deep reddish brown and all drop off within 2 or 3 years after attack.

The mountain pine beetle has a single annual generation. Adults begin emerging in July, though the early emergence is sporadic and irregular. Emergence gradually increases through late July and early August, and usually reaches a peak for 5 to 10 days about the middle of August, unless interrupted by low temperatures. Females attack live trees shortly after emergence and construct egg galleries in the phloem. The beetle develops beneath the bark; it is outside the tree only during the emergence and attack period.

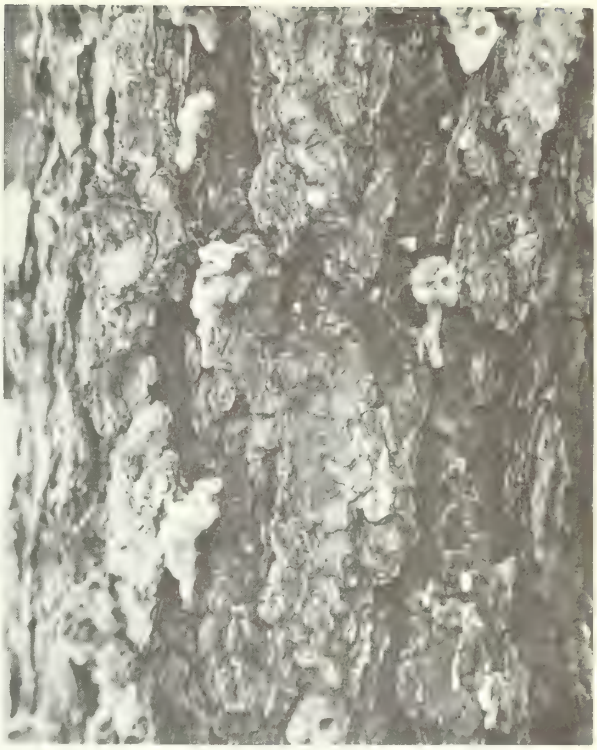

Figure 5.—Pitch tubes on ponderosa pine resulting from attack by mountain pine beetle.

Infestations can balloon at alarming rates. A Forest Service survey during a major buildup in 1963 showed that one infested tree was producing enough beetles to kill six more trees.

Control

Various direct-control methods have been attempted, including chemicals such as an emulsion of ethylene dibromide (EDB) or a 1.5 percent lindane-diesel oil solution. Spraying can begin as soon as spring weather permits, but should be discontinued when about half the population has reached the adult stage. Treatment may be resumed when the flight is over and continued as long as winter travel to the trees is practical. Cacodylic acid (dimethylarsenic acid), an herbicide, has shown promise of control in several recent trials. When introduced into the sap stream of a tree, cacodylic acid either kills the beetles outright, makes the environment unsuitable for them, or both. Be-

cause acid-treated green trees are attractive to beetles under certain conditions, they have been used experimentally to reduce beetle populations by setting up fatal "attractant centers." Application of chemicals for any purpose should be confined to those formulations and methods recommended by specialists and appropriately registered at the time their use is proposed; forest pest control specialists should be consulted whenever direct control is contemplated. (See precautionary statement concerning pesticide use which appears inside the back cover.)

Other control methods, such as piling and burning have also been used. High temperatures (more than 160° F) are fatal to the beetle. Slash piles covered with clear plastic during warm seasons will probably reach temperatures high enough to afford some control. Once the slash is piled, plastic covering costs little extra. Small area treatments, such as around home construction, seem well suited to this technique.

Logging infected trees by conventional methods before the midsummer beetle flights is a feasible control when large-scale outbreaks create sufficient volumes per acre. For areas not accessible by conventional methods, but where beetle control is necessary, helicopter salvage logging may prove successful. Large-scale control by any method is expensive. But helicopters offer, among several advantages, a chance to utilize the wood in infected trees.

There is always some degree of natural control. Two of the most abundant predaceous insects are the redbellied clerid beetle *(Enoclerus sphegeus* Fabricius) and a fly (*Medetera aldrichii* Wheeler). The clerid adults feed on the beetles, each consuming up to one per day, during the emergence and attack period. The clerid larvae feed on all stages beneath the bark—as many as 15 have been found per ft^2 of bark. Only the larval stage of the Medetera fly is predaceous, but each fly larva can consume as many as 10 beetle larvae. Other predators of the beetle, such as woodpeckers and some other predaceous insects, become more numerous during periods of high beetle populations. However, these predators provide only moderate assistance in a control program. They do not provide effective and dependable economic control in themselves. Although extremely low autumn and winter air temperatures may prove fatal to a high percentage of bark beetle broods, the infrequency of low temperatures makes them a relatively undependable control factor.

The ultimate goal would appear to be silvicultural management designed to prevent rather than control epidemics. Among the kinds of stands most susceptible to attack are the overdense, low-vigor pole or small sawtimber classes. The timber sales and thinnings which are currently being made in such stands are major steps toward reducing the likelihood of future epidemics in those areas. A thrifty stand of vigorously growing trees is not so susceptible to bark beetle attack.

Pine Engraver

General Description

Commonly referred to simply as Ips or pine engraver, this beetle is another potential threat to pine stands in the Black Hills. The danger from it, however, is generally localized and short-lived. Wygant and Lara (1967) and Sartwell et al. (1971) have given a complete description of the insect and the damage it causes.

Slash is ordinarily the preferred host material, and pieces larger than 2 inches in diameter are most commonly attacked. When the population becomes so large that available slash will not house them all, some Ips are forced to attack nearby leave trees. Diameter classes from 2 to 8 inches are most often involved. An adult beetle and examples of the pine engraver's galleries are shown in figure 6.

For unknown reasons, outbreaks do not always occur under conditions that appear favorable to the beetles. Ten years or more may pass with no attacks in thinning and logging areas. The beetle is always present, however, and can increase rapidly to destructive levels.

Control

The probability of Ips population buildups can be reduced by (1) continued logging or thinning operations that maintain a uniform amount of slash on the ground, (2) concentration of these operations during the late summer and fall (slash may dry enough to make it unsuitable for beetle occupancy before spring emergence occurs), or (3) prompt salvage of windthrown and fire-damaged trees. When examination of breeding material indicates the presence of a large beetle population (where 150 or more adults can emerge from each ft^2 of infested bark), beetle numbers can be reduced by bunching and burning or chipping the slash. Pieces of slash larger than 2 inches in diameter can be sprayed with a 0.25 percent solution of gamma isomer of benzene hexachloride in fuel oil (Wygant and Lara 1967).

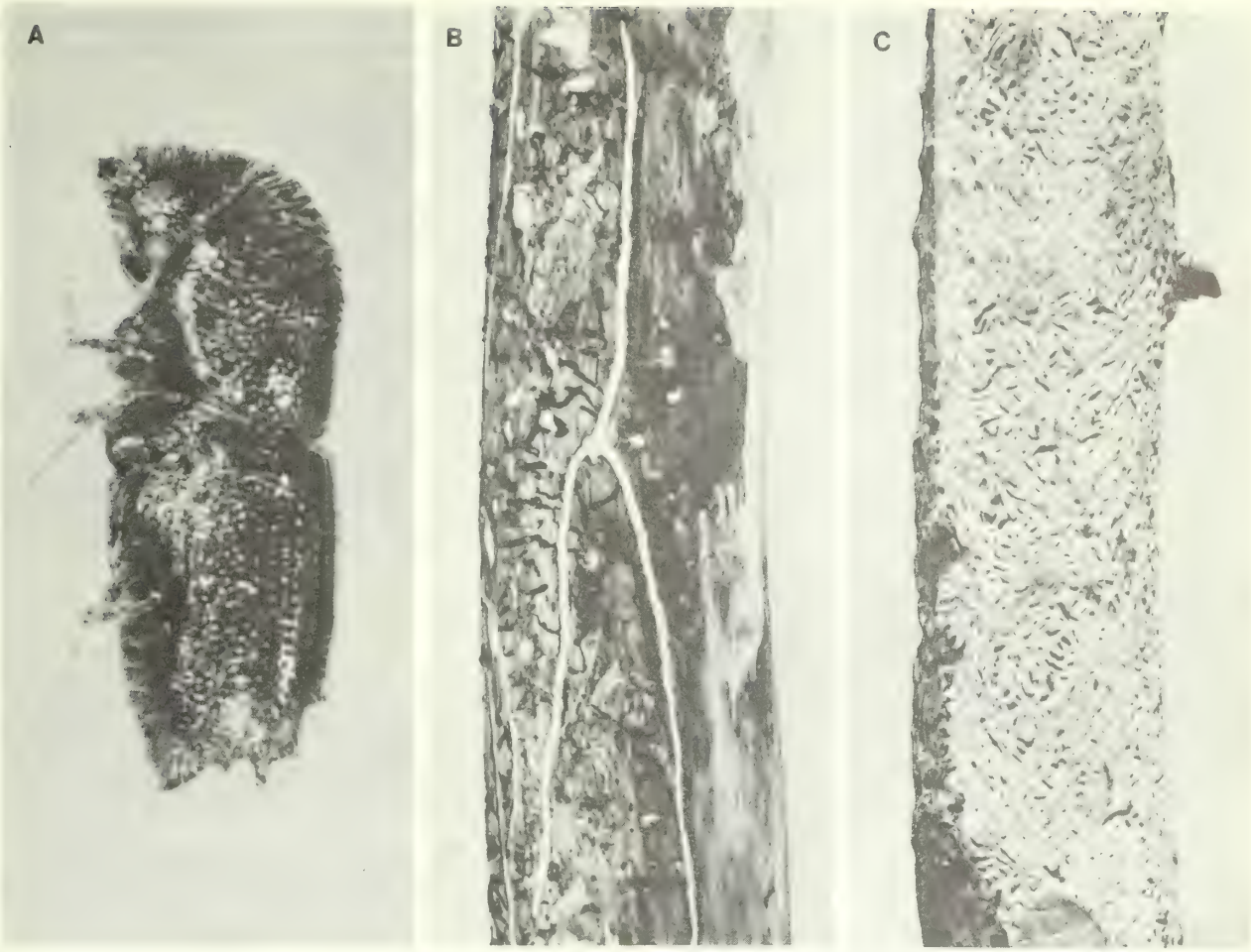

Figure 6.—Pine engraver: *A*, adult; *B*, breeding galleries in ponderosa pine; *C*, feeding galleries in ponderosa pine.

Red Turpentine Beetle

General Description

This beetle, whose size, host preference, and range are the largest of all species in the genus *Dendroctonus*, also is found in the Black Hills. Commonly called the red turpentine beetle (fig. 7a), it is usually not a direct cause of mortality among pines in this area. More often it is a secondary factor, attacking trees that have been weakened by other insects, fire, lightning, logging, or drought (especially on poor sites). Occasionally, however, it does make the primary attack, lowering the trees' vigor and making them more susceptible to damage by other species. Smith (1971) and Eaton and Lara (1967) provide good coverage of the information about this insect.

Standing trees 1 inch in diameter and larger may be attacked. Weakened trees are most often attacked, but those close to freshly cut stumps or green logs are also susceptible. The most conspicuous external indicator of damage is the large whitish pitch tubes the beetles make on the bark surface when they enter the tree (fig. 7b).

The tubes are usually found on the lowest 6 ft of the bole, but may occasionally be seen up to a height of 12 ft. Other damage indicators are small pitch balls and/or coarse reddish frass lodged in bark fissures below the point of attack, or on the ground.

Beneath the bark the pattern of the galleries of this species is distinctive (fig. 7c). The large longitudinal egg galleries and broad larval chambers excavated between the bark and wood distinguish the work of this from other

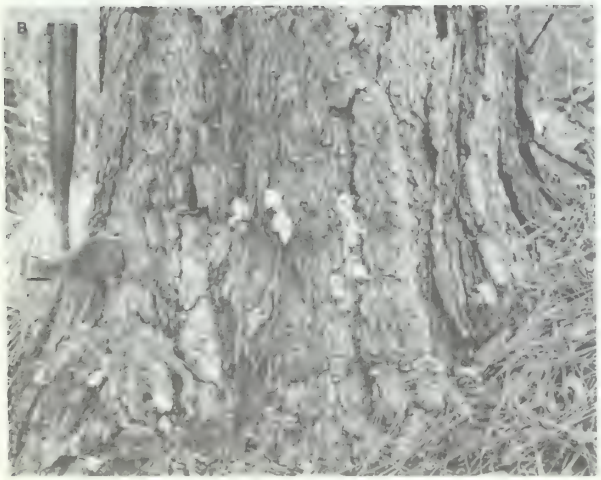

Figure 7.—Red turpentine beetle: *A*, adult; *B*, pitch tubes; *C*, adult gallery and eggs in inner bark of ponderosa pine.

bark beetles. The phloem and sapwood around these galleries are usually heavily bluestained because the beetle is a vector of various fungi, yeasts, and bacteria.

When adult beetles emerge, they may fly for 10 or more miles to attack new hosts. The female begins the attack and is then joined there by the male. The egg gallery is excavated in the phloem, generally proceeds downward, and is partially filled with frass. The eggs hatch in 1 to 3 weeks, and the young feed gregariously in the phloem away from the gallery. In doing this, they form a fan-shaped cavity with an irregular margin. The cavity may range in size from a few inches^2 to more than a ft^2. When the larvae are fully grown, they make separate cells in which they pupate and transform into adults. The new adults emerge from the pupal cells by boring through the bark. The number of generations per year usually ranges from one to three.

Control

Damage can be minimized by cultural practices that keep trees growing vigorously. Among the practices to be avoided are injuries to roots or stem, deep fills or flooding over the roots, and piling green logs or timber near live trees.

Benzene hexachloride is an effective insecticide with a long residual effect. This chemical, when sprayed on the bark in an oil solution, kills some of the insects in the tree and will prevent attacks for many months. It may also be applied to infested stumps to kill emerging beetles. All chemical applications should be made on the basis of recommendations by experts in that field. Acceptable methods and formulations are changing rapidly.

Pine Tip Moth

Pine tip moths are pests of small trees. At least two species of the moth, *Rhyacionia bushnelli* and *R. neomexicana*, are likely present in the Hills. The damage is usually neither spectacular nor serious. In certain special situations, however, it can be important. Repeated loss of leaders in a seed orchard could negate many man-hours of skilled work.

Damage is caused by the larvae mining in the new shoots. As larval development progresses, the infested tips begin to fade. Though repeated attacks tend to cause the trees to become malformed, most trees outgrow the damage. By the time trees are 8 to 10 ft tall, little evidence of damage remains. No research has been con-

ducted on this insect in the Black Hills, mostly because of its small importance here.

Applied control is unnecessary under most forest conditions. In some parts of the country, infestations appear to be associated with low site conditions.

DISEASES

Only a few fungi of importance to the commercial timber grower are found in the Black Hills and Bear Lodge Mountains. Dwarf mistletoes (*Arceuthobium* spp.) are capable of infecting Black Hills pine, but have never been found on trees in this region. Consensus among pathologists is that climatic factors prevent dwarf mistletoes from becoming established in this area.

Red Rot

Red rot (*Polyporus anceps* Pk.), which causes a white-pocket rot, is one of the major causes for loss of sound wood in commercial stands (fig. 8). When losses from red rot are combined with those from the brown cubical rots, percent of scalable defect rises markedly with increasing tree age (Hinds 1971, fig. 4, table 4).

Comprehensive coverage of red rot in ponderosa pine in the Black Hills is included in Andrews' reports of 1955 and 1971. Both immature and mature, and vigorous and declining trees are susceptible to infection. Even though virtually no economic losses are sustained by immature trees, red rot should be considered a disease of all age classes except seedlings and saplings.

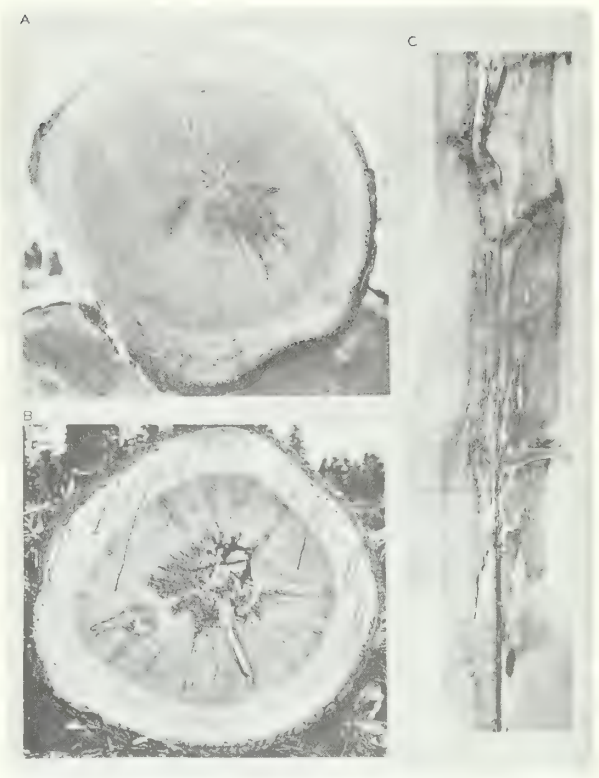

Figure 8.—Appearance of red rot: *A*, incipient decay at end of a saw log; *B*, advanced decay at end of a saw log; *C*, advanced decay bordered by incipient decay in heartwood of a board (the centrally located area of disintegration probably indicates where rot entered the trunk).

Development

Infection becomes established in living trees through the branches. Branches larger than 1.5 inches in basal diameter are 20 times more likely to be avenues through which the infection spreads than are smaller branches. Nearly all the decay develops from airborne spores released by fruiting bodies associated with sap rot of dead material. The sporophores continue to develop annually for about 6 years. The spores lodge in small openings in the bark of dead branches, and probably germinate immediately if moisture is favorable.

After germination, the fungus develops a pad of mycelium between bark and wood, from which the branch wood itself is infected. The infection then spreads toward the bole through both wood and pith of the branch (fig. 9).

Branches can be attacked by red rot fungus from the time they have deadwood (the whole branch need not be dead) until they have been dead about 20 years, provided they have retained their bark. It is very rare for broken, dead branches to become infected. A tree with large, dead, bark-covered branches is a likely candidate for red rot infection (fig. 10).

Since infection occurs through dead branches, the possibility of multiple entrance points throughout the whole tree stem increases with age. Once the rot reaches the heartwood, it may spread up and down the trunk and coalesce with other decay pockets. Thus in older trees the decay may be one long column, many small columns, or a combination of both. There is a lag, however, between the time red rot reaches the heartwood and the development of scalable defect. Hinds (1971) found age classes older than 100 years to have substantially greater percentage of scalable defect due to red rot.

Figure 9.—Longitudinal section through a bark-covered dead branch and adjacent part of the trunk of a small blackjack exposing red rot that apparently entered at about the point marked by the arrow. Decay had extended as far as the pitchy base of the branch where it had concentrated into slender, highly pigmented columns.

Figure 10.—Large bark-covered, dead branches are likely infection points for red rot fungus.

Detection

Red rot is difficult to detect in living trees because fruiting bodies rarely develop on them, and then only on dead branches where they merely indicate branch decay. The fungus does not require conspicuous entrance courts such as wounds, fire scars, or dead tops. No practical method has been found to identify decayed mature and overmature trees and estimate volume losses before cutting.

In immature trees, dead branches are generally reliable indicators of red rot. Undecayed branches resist pressure or break with a crack. Branches in an advanced stage of decay offer little resistance and break as though waterlogged. Suspected branches must then be pruned flush with the trunk to see whether the knots have been penetrated. Heart rot is likely if red rot occurs in the pith. In immature trees, bark-covered branch stubs usually indicate the presence of red rot.

Red rot can often be identified by the characteristic rot pockets that appear in the pitchy base of the branch. Incipient branch decay can be recognized by a continuous white mycelial pad (fig. 11), that binds bark to wood so tightly that pieces of wood stick to the bark when it is peeled off.

Control

Incidence of infection by red rot can be reduced by sound silvicultural practices. Prun-

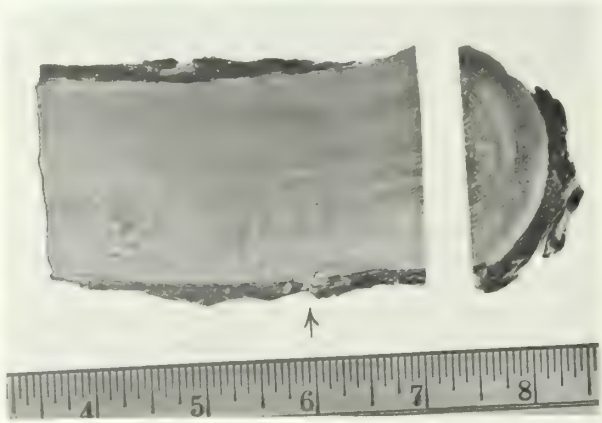

Figure 11.—Cross sections of a dead branch about 2 years after it was inoculated with red rot fungus at a point indicated by the arrow. The incipient stage in the upper half of the longitudinal section is revealed only by a slight discoloration of the wood. The advanced stage in the lower half is characterized by small white pockets running parallel to the grain. The irregular white line between the bark and the wood on the upper side of the section is the edge of the fungus pad. The cross-sectional view illustrates rapid radial invasion from the pad.

ing is probably the best cultural treatment in stands where average diameter is small (less than 7 inches). Removing all branches on the butt log in one operation is desirable, though one or more repeat visits may be needed to prune up 17 ft. Pruned branch stubs are rarely the site of infection by red rot. The earlier pruning is begun, the more complete will be protection against red rot.

Intermediate cuts to improve volume growth rates may also help cut down the incidence of red rot when infected trees and those uninfected trees which have many large branches are removed. Stand densities low enough to promote rapid individual tree growth will not necessarily lead to development of large branches.

Western Gall Rust

This rust is the major component of the *Cronartium coleosporioides* complex in the Black Hills (Peterson 1959) and is the second most troublesome disease on ponderosa pine. It is a serious problem in localized Black Hills areas. Peterson (1959) reported cankers occurring below a height of 32 ft on an average of 7 percent of the dominant and codominant trees in an 1,800 tree sample in the Roubaix vicinity. Nearby in the Windy Flats area, from a third to a half of the potential crop trees had cankers. Nearly all trees at Windy Flats bore galls (often hundreds per tree), which had killed branches and deformed trees. The rust affects the form, lumber content, and growth rate of pines, and kills individual trees, but is not known to destroy whole stands. Peterson (1960) provides more detailed coverage of this disease.

Gall rust infects pine of all ages. It is most serious in plantations, where it may kill young trees. Most infections occur on twigs of the current season. When the rust invades pine bark, cambial cells of the pine shoot begin to divide rapidly. The result is a woody gall, soft at first, but later as resins and other deposited materials solidify, the gall becomes harder and more decay resistant than normal wood. Galls usually live only a few years because when they produce fruiting bodies (aecia) they disrupt the host bark and often kill the shoots and stems which bear them.

Cankers are formed on the trunks of trees through infections from branches or wounds, (fig. 12) and may cause mortality. However, many trees survive and appear to sustain only slight growth loss. Loss of merchantable length and mechanical weakness are the main disadvantages of cankers.

Elimination of the disease from timber stands is not possible, but fortunately such action is not needed. The aeciospores are capable of transmitting the disease directly from pine to pine and these windborne spores can be disseminated for hundreds of miles. Prudent thinning of trees containing trunk cankers and pruning lower branches which contain gall minimize the adverse effects of gall rust. Unfortunately, however, vigorous trees are more apt to be infected than weak ones, partly because the greater surface area of new shoots on the faster growing trees provides a greater chance for infection.

Figure 12.—*Peridermium* canker on bole of ponderosa pine.

Experiments with antibiotic sprays and selection of rust resistant pines also offer some promise of control.

Shoestring Root Rot

This root rot is common throughout most of the forested areas of the world. Although it had not previously been considered a serious threat to forest stands in the Black Hills, it has caused locally heavy losses in young plantations and scattered mortality of sapling and pole-sized trees in thinning plots. It may well be an unrecognized cause of mortality elsewhere in the Hills.

The greatest trouble may occur in the first decade after plantation establishment on a cleared area, or after a thinning to create specified stand conditions (Swift 1972). *Armillaria mellea* colonizes roots and stumps, and a high inoculum may be built up in thinned areas.

Infection occurs mainly through mycelial strands, or rhizomorphs, which grow through the soil. They can penetrate even unwounded bark by mechanical pressure, aided by enzyme activity. Infection may result also from root contact. Cultivation to reduce competition from surrounding vegetation may increase the likelihood of infection by injuring near-surface roots of planted trees.

Major symptoms of infection begin with a general decline in vigor or abrupt cessation of growth, followed by yellowing of needles and ultimately death of the tree. Whitish mycelial fans, under the bark near ground line, are characteristic evidence of infection. An abnormal resin flow from the root collar is sometimes so great that the litter and soil are cemented into a hard crust. Fruiting bodies (mushrooms) have been noted in midsummer, usually in clusters on stumps, at the base of standing trees, or from the ground. Occasionally, bark beetles attracted to an infected tree that would eventually succumb to root rot, are thought to be the primary cause of death, but are actually secondary causes.

There are no proven methods of direct control of this disease.

Needle Cast

Needle cast (*Elytroderma deformans* (Weir) Darker) causes some defoliation on ponderosa pine in the Black Hills, but is not a serious problem. It is found most often on trees in sheltered situations, such as bottoms or in thickets of reproduction. Lower crowns and interiors of pole-sized and larger trees are usually affected. Trees moderately infected with needle cast have reduced vigor, and are often attacked by bark beetles (Childs 1967).

Open-growing young trees are seldom injured permanently unless the leader is repeatedly infected. Witches' brooms, denser and more globose than those caused by dwarf mistletoe (for which they are sometimes mistaken), often develop in crowns of trees with average or better vigor after several years of light to moderate infection (fig. 13).

Figure 13.—Witches' brooms on pine infected with *Elytroderma*.

FIRE

Wildfire

Because of its potentially destructive nature, wildfire receives a large measure of attention in pine management. The maximum hazard period is midsummer through fall, although fires can burn in any month in much of the Black Hills.

Timber management activities must be conducted so as to minimize the danger from wildfire, in line with good silviculture and economic operation conditions for the woodcutter. Harvesting heavily branched overstory trees produces a greater volume and weight of fuel than what is generated by thinning and intermediate cuts in trees with smaller crowns. Larger branch and stem components of logging and thinning residues do not break down rapidly in the Black Hills, but needles and fine branches decompose after 1 to 3 years on the forest floor, especially under heavy winter snow cover.

The Black Hills National Forest has developed "slash calculators" which permit them to estimate the amount of slash fuel, in tons per acre, created by precommercial or commercial thinning and sawtimber harvesting.

Fortunately, good silvicultural practice is compatible with a high level of fire protection. Concentrations of slash and debris can be lopped and scattered, or piled and burned when conditions permit, to reduce the fire hazard and improve esthetic appearance. Along important travel zones, fire danger can be reduced to a minimum and visual appearance greatly enhanced by chipping the logging and thinning residues.

Ground fires under stands composed of widely spaced trees are less likely to "crown" than fires under closely spaced trees in untreated stands. Bark is thicker on the lower stem of trees in more widely spaced stands, which improves their chance of surviving a moderate ground fire.

Salvage and recovery of trees in the aftermath of a forest fire can be a difficult problem. Deciding which trees should be cut, since they have a poor chance for survival, and which ones can be safely left are decisions that test the managers' skill.

Amount of crown killed by the fire appears to be a workable criterion for selection. Research done in the Southwest (Herman 1954) has produced guides that may be applied in the Black Hills. Mark for removal all trees with (1) more than 60 percent of the length of live crown killed by fire; and (2) all trees with 51 to 60 percent of length of live crown killed if the fire in the vicinity of the tree was a heavy ground or combination ground and crown fire.

Low-vigor trees may be killed by only a small amount of fire damage, and any tree will die if severe scorching of the bark has killed the cambium underneath, even though the crown was untouched. Live, healthy cambium is white and spongy, while the heat-killed tissue turns brown rapidly and has a sour smell.

Controlled Fire

Little research on the use of fire has been done locally. Perhaps the most serious deterrents have been (1) frequent occurrence of hazardous burning conditions essentially the year around, (2) high probability of abrupt, major changes in fire weather, and (3) the common presence of dangerously large accumulations of forest fuels, the result of fire exclusion and naturally slow breakdown of dead plant material. In combination, these factors tend to make prescribed burning a speculative activity in the Black Hills, even in the presence of high-caliber control capabilities.

In managed stands where trees are widely spaced, advance pine reproduction is likely to become established before it is needed or wanted. Light ground fires may be a useful way to destroy unwanted seedlings while they are small, without damage to parent stands. This approach might also reduce fuel accumulations and provide a measure of control over composition and development of understory vegetation.

A current McIntire-Stennis Cooperative Forestry Research Program with the State University of South Dakota is evaluating prescribed burning as a means of reducing or eliminating tree encroachment into Black Hills grasslands. Results from the study could be helpful in developing guidelines for use of prescribed burning as a silvicultural tool. Specifically, it may contribute to solution of the problem of unwanted advance reproduction.

Perhaps the least promising of the several proposed uses of prescribed fire in the Black Hills is for thinning of overstocked, immature pine stands. The reason, of course, is that the selectivity of fire depends upon the amount of intrastand variation in tree size and fire resistance. Since expression of dominance occurs very slowly in Black Hills pine stands, the typically dense ones are apt to stagnate before they develop enough structure for successful thinning with fire.

WIND AND SNOW

Trees that grow for decades in dense stands tend to have slender stems, poorly developed and distributed root systems, and asymmetrical crowns. Rocky and relatively shallow soils over much of the timber growing sites in the Black Hills provide tenuous anchorage for large trees. Taproot formation, plus extension of roots even into rock fissures helps overcome the disadvantage of shallow soils. When stand density is abruptly reduced by a single drastic intermediate cut, many of the reserved trees are likely to be uprooted, broken, or bent (fig. 14). Existing stands that are too dense for trees to reach merchantability in the desired length of time should therefore be thinned in a series of operations.

Stands that are maintained at highly productive densities from seedling size to end of rotation should be much less susceptible to wind and snow damage. Trees in such stands will presumably develop sturdier stems and better anchorage in response to gradual increases in stress, and so be able to withstand normal wind and snowloads.

Snowbend and breakage occurs more often in sapling and small pole-sized trees. Windthrow is a more common hazard to large pole and small sawtimber sizes.

LIVESTOCK AND DEER

Cattle are responsible for most livestock damage. Trampling as the cows walk along plowed furrows is the most common form. Cattle rarely graze or browse on seedlings. Sheep may browse the tips of very young seedlings. Occasionally cattle will rub on individual small saplings, scraping off bark, and breaking

Figure 14.—Trees in this pole stand were whippy saplings when a tardy first thinning was made. Snowbend took a heavy toll of reserved trees.

branches and stems. Fencing out livestock until the trees are small saplings is the most practical protection.

Deer do not ordinarily browse on pine seedlings to the extent that plantation protection is needed. Trees can recover from random browsing with little loss of growth. The mammal repellents ZAC (Zinc dimethyldithiocarbamate cyclohexylamine complex) and TMTD (tetramethylthiuram disulfide) were tested on browse species in the Black Hills (Dietz and Tigner 1968). Initial successes with these chemicals indicates that long-term protection to pines would be available if needed.

RODENTS AND BIRDS

About 15 genera of small mammals that eat pine seed are found in the Black Hills and Bear Lodge Mountains, but only two, *Microtus* and *Peromyscus,* cause serious seed losses. These mice also can cause nearly complete failures among seedlings in plantations by girdling stems under the snow during winter.

Both cottontail and jackrabbits are known to girdle seedlings or to clip off leaders and succulent branch tips. Frequently, the portion nipped off is not eaten, but left on the ground near the original plant.

Of all the rodents, porcupines cause the most damage to trees. The trees are never completely immune to porcupine depredations—seedling to sawtimber sizes may be attacked (fig. 15). The most desirable trees, dominant and codominant crown classes, are the ones most often attacked (Van Deusen and Myers 1962). Where porcupine activity is heavy, large numbers of plantation trees, not just an occasional individual, have been deformed or killed. Porcupines appear to have no redeeming characteristics, while their potential for damage is high.

Poisoning is probably the most effective method for controlling rodent losses in seedings and plantings. Grain treated with compounds such as zinc phosphide, applied at 1 to 3 pounds per acre, apparently offers satisfactory mouse control. In direct seeding operations, the seeds themselves may be coated with rodenticides.

Damage from porcupines and rabbits can be controlled through use of strychnine-treated salt blocks, installed in bait boxes scattered throughout plantations or natural stands. Bait boxes must be constructed so that larger animals such as sheep, calves, or deer cannot be poisoned accidentally. A few losses of squirrels and other animals that are nondestructive to plantations may be unavoidable.

Birds are not known to cause any serious losses of seeds or seedlings in this area. Of the more than 200 species that have been seen in the Black Hills and Bear Lodge Mountains, about 30 are known seedeaters. The seasonal bird populations and number of species that favor pine seeds are both small.

Seeds used in direct seeding operations are coated with aluminum powder to make them less subject to bird losses. Some minor seed losses may occur from birds such as red crossbills and black-capped chickadees taking seeds out of tree-borne cones. Natural reproduction is normally too abundant for such seed losses to be important.

Sapsuckers sometimes bore into ponderosa pine stems to expose the tender tissues of the inner bark, an important component of their diet.

SITE QUALITY

SIGNIFICANCE

Site index is the best method presently available to Black Hills foresters for objectively rating the productive capacity of their forest

Figure 15.—Porcupine damage to ponderosa pine: *A*, seedling—the extensive chewing will ultimately kill it; *B*, pole—merchantability will be limited to a point just below the damage, even though damage probably will not kill the tree.

sites. Two techniques for estimating site quality in the Black Hills give numerical indexes.

Intensive timber management including harvest, regeneration, intermediate cuts, and perhaps even pruning, will depend heavily on a priority-for-action rating so long as financial and manpower resources are limited. Action priorities for any given cultural practice should be based on site quality estimates—the best sites receiving needed treatments first, with lower sites in correspondingly lower priorities.

CONVENTIONAL DETERMINATION

Site index can often be readily determined from the conventional height-over-age curve relationships. Curves prepared under the direction of Hornibrook are suitable for Black Hills pine stands where age of the index trees is at least 70 years and where past crowding has not materially restricted height growth (fig. 16). The height-age relationship can be affected by suppression, as shown by a 70-year-old, naturally stocked stand of about 2,800 trees per acre (4-ft spacing), which underestimated site index by 15 ft. Some reduction in growth from competition can be expected from nearly all stands old enough to use the conventional form of index estimation. Some trees in Hornibrook's sample were adding on more than 20 rings per inch.

Data for Hornibrook's site curves came from nearly 400 trees located at 20 widely separated areas in the Black Hills region. He classified them as vigor class "B" trees which were still making height growth, and had the following general characteristics: "fair to moderately vigorous crowns with average width or narrower, and length less than 55 percent of total

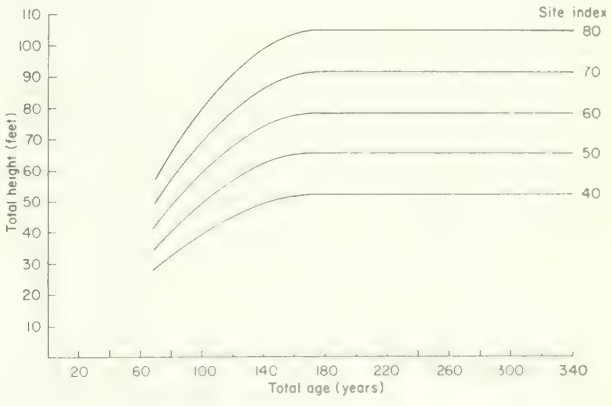

Figure 16 —Site index curves for ponderosa pine.

height; either short wide crowns or long narrow ones, but not sparse nor ragged; occasionally flat on one side; position either dominant or codominant but sometimes isolated."

Height measurements (to the nearest ft) and age counts made from borings taken at the base of the tree should be averaged for several trees when site index curves are used. These averages provide an integrated index value which applies over the area occupied by the trees. Increasing the number of trees measured on a sample area increases the reliability of site index estimates. However, the little improvement in sampling error gained by measuring more than six trees is more than offset by the difficulty in finding suitable trees and the time required for measurements. All trees sampled should be free from diseases or mechanical damage to the upper bole and meet the standards for Hornibrook's vigor class "B".

ESTIMATES FROM SOIL AND TOPOGRAPHY

Very commonly in the Black Hills, the conventional method of site index estimation cannot be used. Either there are no trees present, or the ones that are present are unsuitable for measurements. Site index for crystalline or limestone areas may be estimated from tables 1 and 2 using soil and topographic parameters (Myers and Van Deusen 1960b). Use table 2 where estimates are desired for sites on the hogback ridge. Equations from which the tables were derived may be useful, especially where data are being computer processed. The equations are given in Myers and Van Deusen (1960a).

Two special topographic situations may be encountered in the field, and should be handled in these ways:

1. All bottoms, whether main or side valley, should be called 0 percent of the distance upslope.
2. Sloping ridges with tops more than 3 chains wide should be measured as slopes. A ridgetop should be classified as 100 percent up the slope only when the ridge line is approximately level or less than 3 chains wide.

Suppose a forester planned to plant trees on a burn, but he decided not to put them on any site with an index less than 50. One portion of the burn involved an entire hillside, from creek bottom to ridgetop. Average gradient of the slope was 30 percent and it faced generally east. The upper quarter of the hillside consisted of exposed metamorphic rocks with soil that was obviously only a few inches deep. Downslope from the rocky area, soil depth was unknown.

Two or three scattered soil pits dug below the rocky upper slope each exposed soil depth of at least 20 inches—digging stopped at that depth. Table 1 indicates the site index to be at least 51, probably higher, depending on how deep the soil actually was. Since soil depth normally increases from ridgetop to slope bottom, all of the slope from creek bottom to rocky area at

Table 1.--Site index of ponderosa pine (in ft) in the crystalline area of the Black Hills and Bear Lodge Mountains, northwest and southeast slopes[1]

Distance upslope and soil depth	Site index when slope percent is--				
	0	10	30	50	70
	Feet				
0% upslope:					
5 inches	53	51	49	--	--
10	58	56	54	--	--
15	61	59	57	--	--
20	63	62	59	--	--
30	67	65	62	--	--
40	69	68	65	--	--
60	73	72	--	--	--
30% upslope:					
5 inches	49	48	46	44	42
10	54	53	50	48	46
15	57	56	53	51	48
20	59	58	55	53	50
30	62	61	58	56	53
40	65	64	61	58	55
60	69	67	--	--	--
60% upslope:					
5 inches	46	45	43	41	39
10	51	50	47	45	43
15	54	52	50	48	45
20	56	55	52	50	47
30	59	58	55	52	50
40	61	60	57	54	52
100% upslope:					
5 inches	43	42	40	38	36
10	47	46	44	42	40
15	49	48	46	44	--
20	51	50	48	46	--
30	54	53	50	--	--
40	56	55	52	--	--

[1]Add 1 ft for north and east slopes, and 2 ft for northeast slopes; subtract 1 ft for south and west slopes, and 2 ft for southwest slopes.

Table 2.--Site index of ponderosa pine (in ft) in the limestone area of the Black Hills and Bear Lodge Mountains

Soil depth (inches)	Site index when distance(percent) upslope is--										
	0	10	20	30	40	50	60	70	80	90	100
	Feet										
5	--	--	--	--	--	--	--	40	39	38	37
8	--	--	--	--	--	--	--	44	43	42	41
10	--	--	--	--	50	49	48	47	45	44	43
13	59	58	56	55	53	52	50	49	48	47	45
15	61	60	58	56	55	53	52	51	49	48	47
20	65	63	62	60	58	57	55	54	52	51	50
25	68	66	64	63	61	59	58	56	55	53	52
30	71	69	67	65	63	62	60	58	57	55	54
35	73	71	69	67	65	64	62	60	59	57	56
40	75	73	71	69	67	66	64	62	60	59	57
45	77	75	73	71	69	67	65	64	--	--	--
50	79	77	74	72	71	69	67	65	--	--	--
55	80	78	76	74	72	70	68	66	--	--	--

75 percent upslope could be planted, since it would meet the minimum site index of 50. If there were any doubt about lower slope conditions, more holes could be dug. At 30 percent upslope, a soil depth of only 9 to 10 inches would meet the minimum of site index 50, providing other topographic factors remained the same.

Estimates of site index made from soil and topographic factors are strictly applicable only to the point sampled. The more variable the site is, the more points should be sampled to accurately characterize site quality over the entire area. Quite often all that is needed, however, is an index estimate from what appears on the ground surface to be the extremes in quality.

GROWTH, YIELD, AND QUALITY IN MANAGED STANDS

A roundup and critical analysis of all that has been learned about growth, yield, and quality in Black Hills ponderosa pine leads to the following generalized assessment of the state of our knowledge:

1. Much has been learned about growth responses of trees and stands to single thinnings in overstocked, even-aged, immature stands. We can predict responses across a wide range of stockings and size classes. Influence of site quality on these responses is predictable only in general terms.
2. Preliminary information has been obtained on potential growth and development of trees and stands under prolonged, intensive culture, begun early.
3. Less is known about potential yields, both intermediate and final, in continuously cultured stands.
4. Some good information has been obtained on changes in vertical distribution of increment, hence in stem form, of immature trees released from crowding by light to moderate, single thinnings. Little is known about long-term effect of continuous culture on stem form.
5. Some good, but limited information is available on technical properties of stemwood from fast- and slow-growing trees in thinned and unthinned stands.

PAST RESEARCH ON GROWTH

Results of early, unreplicated studies of thinning and growth in the Black Hills, started between 1906 and 1931, showed that:

1. Thinning of overstocked stands can be expected to improve growth of reserved trees in diameter, volume, and, in most cases, height—even in stands which have been stagnant for several decades.
2. Growth responses tend to be roughly proportional to the relative change in degree of competition produced by thinning. However, none of the early thinning trials included treatments severe enough to reveal potential growth rates for free-growing trees.

3. One-shot precommercial thinnings which leave about 600 1-inch trees, 400 2- to 3-inch trees, and 300 5-inch trees will effectively control subsequent mortality, allow full utilization of the volume growth potential of "average" sites, concentrate increment on the better growing stock, and stimulate improved rates of height and diameter growth for one or two decades (Myers 1958, Myers and Van Deusen 1960a).

Related research, during the 1950's and 1960's, showed that:

1. Release of trees from severe crowding not only increases periodic rates of lower bole diameter growth, but also increases the overall length of the diameter growth season in some years; rate of height growth also increases but with no accompanying change in seasonal duration. Moisture is the environmental factor which most frequently limits tree growth in the Black Hills (Van Deusen 1968).
2. Future basal area, ft^3 volume, and average d.b.h. of existing immature stands can be estimated satisfactorily by regression, using stand and site data from temporary plots as independent variables (Myers and Van Deusen 1961).

CURRENT RESEARCH ON GROWTH

In recognition of the need for more information on control of growth and yield by thinning, and for prediction of responses—particularly for intensively cultured stands—an elaborate study of growing stock levels (GSL) was installed on the Black Hills Experimental Forest in 1964. The local study is part of a coordinated, Westwide investigation of stocking in even-aged ponderosa pine (Myers 1967). Although in its early stages, the study is nevertheless generating some new information—notably data on tree and stand behavior at the low end of the stocking spectrum. The study samples a wide range of stocking levels (fig. 17). Rethinnings are to be made at 10-year intervals to return stands to assigned nominal levels of stocking, with actual reserve stand densities depending on average stand diameter at time of treatment. Tree measurements and stand inventories are to be made at 5-year intervals.

Plots were remeasured for the second time and rethinned for the first time in the winter of 1973-74. Data from this latest remeasurement had not been analyzed completely when this Paper was prepared. However, enough computations had been made to permit a partial report

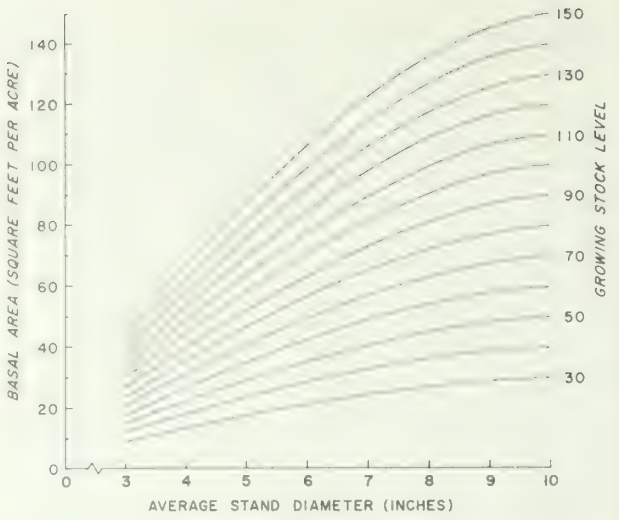

Figure 17.—Standard growing stock levels for ponderosa pine, as established for testing in the Westwide stocking study.

of results at the end of the first decade.

There is evidence that, given adequate growing space and time to capitalize on it, Black Hills poles and saplings can grow fast enough to significantly increase average stand diameters (fig. 18). Across the full range of stocking levels being tested, average 10-year diameter increments for the Black Hills stands were on a par with increments reported for stands of the Interior type in Oregon and Arizona (Barrett 1970, Schubert 1971).

Ten-year basal area increments in the Black Hills stand (fig. 19) were generally somewhat smaller than reported for the Oregon and Arizona stands. This is not surprising, since the latter stands grew on better sites, with index

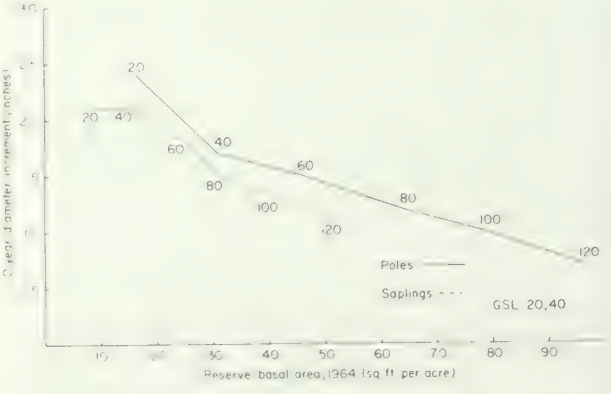

Figure 18.—Ten-year diameter increment for pole and sapling stands thinned to six different levels of stocking in 1964: Black Hills ponderosa pine. (Each plotted value represents average reserve stocking and increment for three replicate plots.)

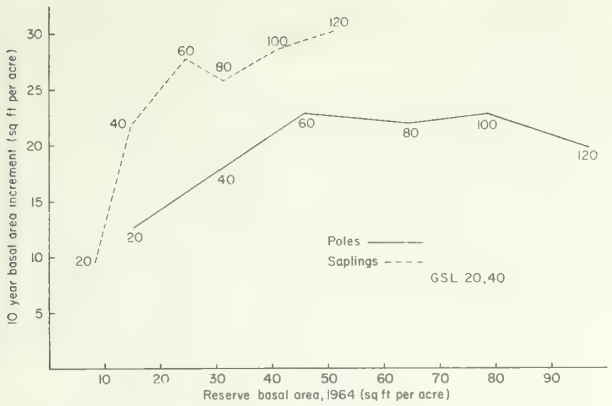

Figure 19.—Ten-year basal area increment for pole and sapling stands thinned to six different levels of stocking in 1964: Black Hills ponderosa pine. (Each plotted value represents average reserve stocking and increment for three replicate plots.)

values about 20 ft higher than the Black Hills sites. More important is the fact that stands maintained at GSL 60 produced practically as much basal area increment as stands at any higher level of stocking. Total ft^3 volume increments followed the same pattern.

Growth responses to repeated thinnings have been indicated by a small-scale demonstration of "sequential thinning" on a single Black Hills site of above-average quality (Boldt 1970). Two thinnings in rapid sequence—the first moderate, the second severe, only 7 years later—transformed a stagnant stand of saplings into a thrifty stand of small sawtimber in only 11 years.

RESEARCH ON YIELDS

The first documented study of yield prediction in the Black Hills was completed by Bates in 1915.[4] He emphasized comparative productivity of the major soil types. During the 1920's, administrative studies of growth and projected yields in cutover stands were made on both the Harney and Custer National Forests.[4] In 1939, Hornibrook published preliminary yield tables for selectively cut stands. A year earlier, Meyer (1938) published his classic yield tables for even-aged ponderosa pine, which included some data from the Black Hills. However, these yield tables were not for managed stands.

Yield tables for managed stands are the basis for timber management planning. Field and computer procedures for preparing yield tables for managed stands have been prepared by Myers (1971) to simulate growth of even-aged stands from regeneration to harvest. The simulation program produces a series of yield tables for different combinations of growing stock levels, cutting cycles, and rotation ages which estimate outcomes in relation to cultural treatments. These procedures were developed from field data on past growth in relation to stand density, age, and site quality obtained from a large number of temporary plots in existing stands of Black Hills ponderosa pine. The GSL study, when completely analyzed, will provide benchmark checks on Myers' predictions of growth and yield in managed stands.

STEM FORM

Manipulation of stocking and live-crown pruning are known to influence stem form of forest trees (Larson 1963, 1964). The principles involved are relatively simple, particularly as they apply to conifers.

The live crown of a tree plays a dominant role in determining the form of the stem which supports it. Maximum diameter increment in the stem is normally added near the base of the live crown. Below this zone, the stem segment free of live branches tends to be relatively cylindrical, except for butt swell. Hence, the bulk of the taper is confined to the segment above the zone of maximum increment, within the live crown. Any factor that significantly alters the size of the live crown and its distribution over the length of the stem can thus be expected to alter the location of the zone of maximum increment and the proportion of the stem length with maximum taper.

Both thinning and live-branch pruning influence crown size and its distribution over the bole. Open-grown trees or stand-grown trees at wide spacings tend to have large crowns occupying a relatively large proportion of their total stem length. As a result, such trees typically have short segments of cylindrical stem and long tapered segments. Closely spaced trees, on the other hand, normally have smaller, shorter crowns due to natural pruning and, consequently, longer segments of essentially cylindrical stem.

In general, then, thinning increases crown width and length and increases stem taper. Pruning has essentially the opposite effect—it reduces both crown length and taper.

Results of Myers' (1963) local study of vertical distribution of annual increment in thinned ponderosa pine generally conformed with these

[4] *Unpublished reports on file at Rocky Mountain Forest and Range Experiment Station, Rapid City, South Dakota.*

principles. However, the pronounced basal shift in the zone of maximum increment which Myers detected was short lived. His analysis of increment showed that the duration of the shift was only 3 to 6 years in most trees, which was roughly equal to and coincidental with the period of maximum overall growth response to thinning. Myers interpreted the downward shift in zone of maximum increment as a response to increased wind stress in boles of released trees.

STEMWOOD PROPERTIES

Most of the wood harvested from Black Hills forests in the past century has come from trees which grew slowly in crowded stands. Because recent research has shown that Black Hills pines can grow rapidly, wood processors and users have questioned whether rapidly grown wood is apt to have the same technical properties as the slowly grown wood which they have been accustomed to handling. No conclusive answer is available yet, but preliminary research suggests that an increased growth rate is unlikely to cause major changes in wood properties (Boldt and Markstrom 1972).

Analysis of stemwood samples from pole-sized trees in thinned and unthinned portions of a typical second-growth stand showed that: (1) thinned trees had significantly wider rings at all heights from 0.5 to 28.5 ft; (2) there were no significant differences in specific gravity, percent latewood, or percent extractives in wood from the two groups of trees; and (3) the wood from the unthinned trees had slightly, but significantly longer fiber tracheids.

SILVICULTURE AND MANAGEMENT

MANAGEMENT DECISIONS

There are a number of important decisions that the forest manager must make to impart a sense of direction and purpose to the forest enterprise—and to his management team. At the very least, he must arrive at definitive answers to these questions:

1. What mix of products, uses, or benefits is the forest to supply?
2. What are the priorities among the various products and uses, based on values and predicted returns? Which will be the dominant use or uses; which will be subordinate?
3. How will the various uses be physically integrated or separated on the ground? Will zones be established in which certain uses will be dominant and, if so, how will they be delineated? What proportion of the forest will be devoted to any single use or mixture of uses?
4. Assuming timber production will be a major use—
   - What compartments or site classes will be allotted to timber crop culture?
   - What kinds of timber products will be grown—pulpwood only; posts and poles only; some mix of all three; or sawtimber as a final crop with intermediate yields of one or more of the roundwood products? What sort of specifications must each of the selected products meet?
   - What level of timber production is to be attained on acres designated for that purpose—full potential, or some reduced level to accommodate associated uses?
   - How long will the timber crop rotation be—the minimum required to mature the desired final crop, or some longer period?
   - What level of management intensity will be maintained? Will the wood production process be closely controlled through frequent entries for treatment and inventory, or loosely controlled with a long treatment-inventory cycle?

Armed with management decisions on these key questions, the silviculturist will be in a strong position to prescribe optimum cultural treatments from among the silviculturally acceptable treatment options.

SILVICULTURAL CONDITION CLASSES

The foundation of any good forest management plan is a pair of descriptive forest models. One describes the forest as it actually exists at the time the management plan is put into effect. The other is an idealistic model which shows how the fully managed forest should be organized and structured to satisfy management goals. Differences between the two models delineate the scope and size of the silviculturist's job.

Basis for these models is a suitably intensive forest resource inventory, designed to determine at least two things: (1) amount and distribution of forest land within each of several land quality classes, segregated on the basis of apparent productivity and susceptibility to management; and (2) the character of the forest growing stock or other vegetative cover on lands in each quality class.

Methods for evaluating the quality of Black Hills forest sites, and guides for their use, are discussed in another section of the Paper. This section describes a simple, utilitarian scheme

for characterizing and classifying vegetative cover for silvicultural diagnosis and prescription. Using the scheme, even an inexperienced forester should find it easy to categorize cover conditions he might encounter in the Hills. Having assigned the condition to a nominal class, he can readily determine the treatment options that research and experience have indicated are appropriate, biologically sound, and environmentally safe. Then, it becomes a matter of technical judgment to select the option that will contribute the most toward overall management goals.

The following simple key may be used to facilitate the first step in the prescription process—condition classification.

Key to Silvicultural Condition Classes in Black Hills Forests

	Class code
TREES ABSENT:	
Recently deforested; signs of previous forest cover clearly evident—	
Site bare of vegetation	09
Site supporting disturbance cover of grass, forbs, or brush	10
No evidence of previous forest cover; permanent or semipermanent park or meadow	11
TREES PRESENT:	
Pine absent or, if present, a scattered or nondominant component in a mixed stand—	
White spruce-pine mixture	05
Pure white spruce	04
Deciduous-pine mixture, pine scattered or subordinate	06
Aspen, aspen-white birch, or bur oak	07
Pine present, in pure stand or as dominant component in mixed stand—	
Pine stand uneven-aged (more than 2 distinct age classes present), usually discontinuous with trees scattered or in clumps	08
Pine stand even-aged, or in transition with remnants of old stand above even-aged regeneration—	
One age (or size) class present—	
Stand immature	02
Stand mature or overmature	03
Two distinct age classes present, parent and progeny	01

Following are more complete descriptions of these silvicultural classes, their variants, and their origins, together with generalized treatment options applicable to each class.

Class Descriptions and Treatment Options

Class 01; Two-Aged Stands

Description.—Stands of this class are called "two-storied" by most Black Hills foresters although the standard definition of the term specifically excludes stands in the process of regeneration (Society of American Foresters 1958). Such stands occupy slightly more than half of the stocked commercial forest acres in the Hills, making them the most widely distributed and most frequently encountered of the several classes.[5]

The two-age or "two-story" structure is a transitory stand condition, representing an overlap between successive even-aged crops. A typical stand of this class is comprised of a light reserve of mature or overmature sawtimber trees scattered irregularly above a well-stocked stand of young pines.

Sawtimber stocking in the upper "story" of a typical stand will usually be quite variable, both in amount and distribution, but over large areas it is likely to average about 3,100 fbm and 35 ft^2 per acre. On all but the very best sites, the upper limit of overstory stocking will probably be about 70 ft^2 of basal area. Beyond that level, if the trees are uniformly distributed, there will usually be too few seedlings established to form a coherent lower story.

Large variations in stocking are also common in the subordinate stands, but overstocking is the normal condition. Frequently, the development of these lower story stands has been severely retarded by heavy and prolonged competition from within and above. As a result, it is not unusual to find "reproduction" stands as old as 50 to 60 years which have not yet advanced beyond large seedling or small sapling size. Trees in such stands generally tend to be slender and whippy, with weak, sparse crowns. The largest and most vigorous trees, or groups of trees, are usually those growing on microsites which are least influenced by competition from the overstory. Where overstory stocking is light and irregularly distributed, there may be enough of these better-developed trees to form a new crop of fair to good quality, after overstory removal and precommercial thinning. In

[5] *Unpublished Timber Management Plan for Black Hills Working Circle, USDA Forest Service, 1963.*

other cases, there may be a critical shortage of good crop trees. Snowbend and windthrow are the principal threats to tall, whippy trees after release.

Origins.—Most of the two-aged stands in the Black Hills have developed in response to repeated partial harvest cuttings. A few of them have resulted from moderate to heavy natural mortality in uncut old-growth stands, brought on by combined impacts of bark beetles, wind, and lightning.

On National Forest land, at least, two-age stands of recent origin are in the minority, simply because the heavier initial partial cuts which triggered regeneration were made several decades ago in most stands. Subsequent partial cuts, made from the mid-1920's through the early 1960's, were largely light selection cuts in stands which had received their first shelterwood cuts 2 or 3 decades earlier (fig. 20). For more detail on past harvest cutting practices in the Black Hills, see the section on regeneration cuttings.

Figure 20.—Steps in the evolution of a typical two-storied stand: *A*, 1931, after first partial cut; *B*, 1967, 10 years after a second partial cut.

Treatment options.—The silviculturist has little freedom of choice in dealing with most two-age stands. Ordinarily, the overstory will be made up of old, yellowbark trees which are growing slowly, losing volume and value to defects, susceptible to mortality agents, and generally ripe for harvest. Development of the understory stand is probably being heavily penalized by the presence of the overwood, even though it amounts to only a few large trees per acre.

Consequently, if the replacement stand is stocked with at least 600 well-distributed trees per acre of fairly good vigor and quality, mostly 3 ft tall or taller, the only reasonable prescription is complete overstory removal, followed by a precommercial thinning.

To improve appearance and minimize fuel buildup, the thinning may well be delayed until the slash from the overstory trees has had a chance to lose its needles and settle closer to the ground. A relatively heavy overwood may be removed in two stages, where it is necessary to control fuel buildup and minimize damage to a dense, overdeveloped replacement stand. The second stage should be completed within 4 to 5 years, however.

In those cases where a doghair understory stand has stagnated under severe two-level competition and has little if any potential as a replacement stand, the silviculturist should consider the advisability of destroying it and starting anew. This might be done by clearcutting the overstory, eliminating the residual understory with a brush-chopper or other device, then seeding or planting. Such a treatment should probably be restricted to small blocks where site denudation would not be esthetically objectionable. Under other conditions, natural regeneration may be the better choice. If the latter option is chosen, (1) the overstory stand should be partially cut to leave no more than 10 to 15 good quality, windfirm seed trees per acre; (2) the existing understory should be eliminated; and (3) the site should be sufficiently disturbed to create seedbed conditions favorable to seedling establishment, just prior to a good seed year.

Class 02; Pine, Even-Aged, Immature

Description.—For this classification, an even-aged stand is one in which at least 75 percent of the trees fall within the extremes of a 20-year age range. An immature stand is not yet ready for final harvest, according to management criteria. Age in itself may not be an important factor in judging maturity, except in continuously managed stands.

Stands of this class occupy a little less than half of the stocked commercial forest land in the Black Hills. On publicly owned lands within the class, about 9 out of 10 acres support pole stands while the remaining acres carry stands of seedlings or saplings.

These stands differ from the classical, textbook variety of even-aged stands in that crown class differentiation tends to be slow and stem diameter distributions are apt to be skewed toward the smaller classes at all ages. These traits are structural reflections of the inherent tolerance of Black Hills pine to intrastand competition and its tendency to stagnate.

In stands which are typically dense at the time of establishment, and left to develop naturally, more than 50 percent of the trees may be expected to remain in stem diameter classes below the stand mean d.b.h. from **youth to biological maturity** (fig. 21). As the plotted distributions show, the proportion of trees smaller than stand mean d.b.h. may be as high as 85 to 90 percent in dense sapling stands, and remain as high as 60 percent in large pole stands more than a century old. It is because of the abundance and remarkable persistence of subordinate trees in these stands that thinnings from below are so successful.

Diameter distributions tend to assume a more normal, bell shape in stands which have been thinned moderately one or more times (fig. 22). Heavy thinnings, if repeated, can produce stands with very narrow diameter distributions (Boldt 1970).

In stands that have remained heavily overstocked for several decades, the typical trees have (1) slender, whippy stems with height-

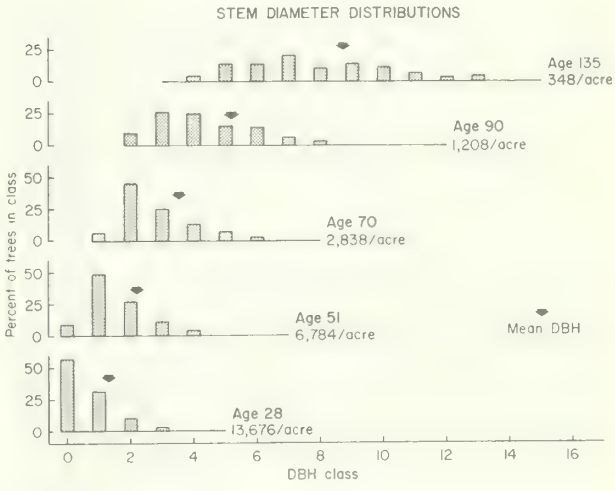

Figure 21.—Stem diameter distributions for typical, dense stands at various ages.

Figure 22.—A classic even-aged, immature stand: 60 years old, thinned lightly in 1934 and again in 1964.

diameter ratios of from 75 to 125+; (2) boles with relatively little taper, and absolute form quotients in the range 0.70 to 0.75; (3) sparse short crowns, usually occupying only 30 to 40 percent of stem length; and (4) poorly developed, often asymmetrical, root systems. Risks associated with these characteristics complicate the selection of trees to leave in initial thinnings.

In contrast, typical trees in uncrowded but fully stocked stands have (1) stems with height-diameter ratios of 60 to 85; (2) more tapering stems with form quotients in the range 0.60 to 0.70; (3) fuller, longer crowns occupying 50 to 60 percent of stem length; and (4) better developed, more symmetrical root systems.

Origins.—The vast majority of stands of this class originated as natural reproduction following heavy harvest cuts, fires, and massive bark beetle epidemics shortly before and after the turn of the century. The remainder has been created by seeding and planting of burns and other deforested sites, and by a few recent complete overstory removals in two-storied stands.

Treatment options.—"No treatment" is a valid option in stands of this class which are (1) properly stocked or understocked according to management criteria; (2) satisfactorily vigorous, healthy, and pest-free; (3) growing at acceptable rates on both an individual tree and stand basis; and (4) comprised largely of trees of acceptable technical quality.

In most other stands of the 02 class which do not meet the foregoing specifications, an intermediate cutting will be appropriate. Purposes of the treatment should be to (1) adjust stocking to a desired level; (2) remove poor-quality, low vigor, under-sized, over-sized, or high-risk elements of the growing stock; and (3) if possible, obtain an intermediate yield of salable rough products. Aids for tailoring prescribed intermediate cuts to silvicultural and management objectives are given in the section on growth, yield, and quality.

In some instances, complete destruction and replacement of an immature stand may be the only reasonable option. This might be prescribed for stands which contain little, if any, acceptable growing stock because of prolonged overstocking, stagnation, and impacts of dis-

ease (gall rust) and weather (snowbend and breakage). There is no point in investing time and money in a hopelessly deteriorated stand, especially if it is occupying a high-quality site.

Reinforcement planting or seeding may be appropriate for small, young stands which are inadequately stocked.

Finally, pruning to enhance stem quality may be prescribed in large sapling and pole stands if the treatment is consistent with management aims and defensible economically. See sections on growth, yield, and quality and red rot for remarks on pruning.

Class 03; Pine, Even-Aged, Mature or Overmature

Description.—As indicated for the previous class, stand maturity must be judged primarily on the basis of product goals. Overmaturity, on the other hand, is primarily a biological condition signaled by such symptoms as cessation of height growth, loss of vigor, reduced diameter growth, and increased susceptibility to disease and insect problems.

On forest properties which have been and are managed for sawtimber as the final crop, stands of this class are uncommon; past harvest cutting has opened most of the older stands sufficiently to stimulate reproduction and produce a two-storied structure. However, the class is widely represented in Black Hills forests by large numbers of "inclusions;" that is, stands which are discrete, but too small in area to warrant segregation and separate accounting in any but the most intensive timber management inventory. Common examples are isolated small patches of yellowbark poles or small sawtimber scattered through a matrix of more extensive stands of the 01 to 02 class (fig. 23). Typically, these are crowded groups of old-growth trees which were bypassed in past harvest cuts for saw logs, because of small stem size and/or poor quality. Some such patches have received light intermediate cuts for posts or poles; many others have not been cut in at all.

On forest properties being managed for large poles or other round products as a final crop, "mature" even-aged stands may constitute a large proportion of the growing stock. For example, large pole stands of the 100- to 125-year age class, with mean stand diameters of 10 to 14 inches, are common and extensive. If by management decision these stands are declared mature and ripe for harvest, they properly belong in this class. Figure 24 shows a typical stand of this kind a few years after it had been given the equivalent of a seed-tree harvest cut.

Figure 23.—A small group of mature poles, 150 years old, left untouched by past harvest cuts in surrounding stand.

Origins.—Most of these stands appear to have originated as reproduction following the killing of patches of mature trees in virgin, old-growth stands by bark beetles, localized wildfires, lightning, and wind.

Figure 24.—Previously dense stand of small sawtimber, 130 years old, a few years after harvest by the seed-tree method.

Treatment options.—Unless management desires to perpetuate existing small inclusions for some special purpose, the silviculturist will probably want to convert them to blend with the matrix stands surrounding them.

If the trees forming the inclusion are substantially larger than the trees in the matrix stand, the best option is to maintain a moderately high level of stocking in the inclusion until the trees in the surrounding stand reach about the same size. Removal of a few high-risk, low-vigor individuals may be the only treatment required during the catchup period. After stand sizes have equalized, the included stand should be opened gradually to match the stocking of the matrix stand, and then may be treated similarly to the end of the rotation.

If the inclusion occurs in a two-storied stand with a lower story of seedlings or small saplings, it should be given a harvest-regeneration cut 10 to 20 years before the overstory removal treatment in the matrix stand. If the inclusion is larger than 3 acres, it should be given a shelterwood seed cut. The overwood should be removed at the same time as the overwood in the two-storied matrix stand. If the inclusion is 3 acres or less, another harvest option is a clearcut, with seeding from the side by overwood trees in the matrix stand. A seed-tree cut should probably be avoided because of the risk of windthrow after drastically opening a previously crowded, older stand.

Treatment options for sub-sawtimber stands which are declared mature by management decision are the same as for biologically mature stands. Trees may be harvested by any of the three even-aged methods; the two-cut shelterwood will be best in most cases. See section on regeneration cutting for general guides and prescription details.

Class 04; Pure White Spruce

Description.—Lack of demand for white spruce wood has largely precluded commercial cultural treatment in stands of this species in the Black Hills. Consequently, most stands are natural in origin and remain essentially natural in condition.

Even-aged stands are by far the most common. However, occasional stands show enough vertical stratification in their structure to be classed as uneven-aged. Evidently, the process of breakup of overmature stands usually proceeds fast enough to result in mass establishment of an even-aged replacement stand. However, in those less frequent instances where breakup occurs more gradually, spruce reproduction is sufficiently tolerant to establish and develop in the resultant small openings.

On the cool, moist sites which it prefers, white spruce is a postclimax type which is capable of maintaining site dominance even in the presence of a ponderosa pine seed source. Not only is spruce more tolerant than pine, but it is also capable of faster height growth during early life, at least in the better spruce habitats. In more xeric situations where spruce is offsite, pine will typically survive better and grow faster than spruce, and will eventually replace or dominate it.

Origins.—Except for man-caused wildfires, selective harvest of pine in pine-spruce mixtures, and possible effects of prolonged fire protection, origin of existing spruce stands in the Black Hills has been little influenced by human activities.

Most plant ecologists familiar with the Black Hills subscribe to the idea that spruce stands were much more prevalent in the area during the early postglacial period, when conditions were cooler and more moist. As the environment has become progressively warmer and drier, spruce has retreated to the milder sites which it now occupies; hence, its designation as a postclimax forest. The natural shrinkage of the spruce type is, presumably, still underway.

Treatment options.—No research has been done on spruce culture in the Black Hills, nor has much been learned by experience. Therefore, the options identified here should be viewed only as promising, but unproven, possibilities.

No treatment will be the only valid option wherever cultural work depends on commercial sale of spruce stumpage for which no market exists.

In overstocked, young stands where management is willing to invest cultural funds, light to moderate precommercial thinnings will be appropriate. No guides can be given for desirable stocking or spacing in such stands, but tolerance of spruce and its preference for mild, moist sites suggest that it may grow satisfactorily at somewhat higher stand densities than ponderosa pine. If properly planned and controlled, Christmas tree harvest may make thinnings economically feasible in some young stands. However, present demand for this special product is limited because few spruce Christmas trees are sent to outside markets.

Intermediate cuts in stands of pole size and larger should also leave higher reserve densities than would be left in pine. Spruce's shallow rooting habit makes it susceptible to windthrow,

especially where heavy cutting exposes formerly protected trees.

If and when harvest cutting becomes feasible in mature spruce stands, a two- or three-cut shelterwood will probably be the safest method. The first cut should probably reserve at least 70 to 80 ft^2 of basal area per acre to minimize blowdown in the overwood.

Where the management objective is to convert a spruce stand to pine or some other species, the proper approach, obviously, will be a complete clearcut of the spruce. If the stand is 5 acres or less and is surrounded by a pine stand of seed-bearing age, the opening can probably be regenerated naturally. Otherwise, seeding or planting will be required, at least in the central portion of the clearing.

Because of the high incidence of rot defect in most of the older spruce that has been cut in the Black Hills, that species should probably be managed on a pathological rotation of 125 years or less.

Figure 25.—Young, mixed stand of spruce and pine on the margin of a burn.

Class 05; White Spruce-Pine Mixture

Description.—Most commonly, stands of this class are distinctly two-storied. Upper story trees are usually of sawtimber size, either all pine or mostly pine, forming an overwood of low to medium density—5 to 50 ft^2 of basal area per acre. The lower story is pure spruce or a spruce-pine mixture of seedling, sapling, or pole size, even-aged, and typically well stocked to overstocked.

A less common variant of the class is a single-storied, intimate mixture of pine and spruce with trees of both species about the same age and stature (fig. 25). This structural condition tends to be limited to young stands and is temporary, since one species or the other will ordinarily assume dominance with advancing stand age. On sites favorable to spruce, trees of that species will ultimately overtop and suppress associated pines. Conversely, on warmer, more xeric sites, the pine will normally assume dominance. However, the tolerant spruce may persist for many years as a subordinate stand component, giving rise to a two-storied structure. Pine heavily suppressed by spruce, on the other hand, is more likely to drop out of the mixture.

Origin.—Stands with an overstory of mature pine and an understory of young spruce, or spruce and pine, typically result from opening up a well-stocked pine stand on a mild site in the presence of a nearby spruce seed source. Composition of the understory is simply a reflection of relative regeneration success for the two species. The reduction in overstory stocking may be caused by partial cutting, heavy selective killing by bark beetles, or natural breakup of an overmature stand.

The young, even-aged mixtures typically establish in newly created forest openings which have both pine and spruce seed sources on their margins (fig. 25). Removal of the overwood in a two-storied stand with a mixed understory produces a similar result.

Treatment options.—In two-storied stands with a pure spruce understory, the silviculturist may opt to (1) remove the pine overwood and culture the young spruce stand; (2) perpetuate, for a time, the two-story structure; or (3) somehow eliminate the spruce and work for a new stand of pine regeneration. Where the understory stand is of mixed composition, essentially the same options are open, but the silviculturist may also have to decide which understory species to retain and which to eliminate.

If management strategy should favor option 2, the silviculturist may find it necessary to reduce stocking in both the overstory and understory to achieve and maintain a healthy stand. Of course, stocking control is almost certain to be needed, also, in the immature stands that would result from implementing either of the other options.

Valid treatment options for the young, even-aged mixtures include (1) no treatment if

stocking and composition are satisfactory; (2) cleaning or weeding to hasten attainment of dominance and improve growth of one species favored by management strategy; and (3) thinning to wide spacings that may permit maintenance of a mixed stand despite differential growth rates between species.

Class 06; Deciduous-Pine Mixture, Pine Scattered or Subordinate

Description.—In these stands the major tree component is a hardwood. Normally, the hardwood component is solely aspen or bur oak. The pine usually occurs as scattered individuals throughout the stand, or may sometimes be found in small pockets of more or less mature trees. Crowns of the scattered pines may be either above or below the relatively low crown canopy of the deciduous species. Because of the seral nature of this class, its appearance may range from the early beginnings of sprouts to full grown oak brush or aspen trees.

Origin.—Most commonly, this class develops as a result of extensive destruction of an existing pine stand. Fire is probably the most frequent causal agent, although bark beetles or tornadoes may be responsible. Occasionally a heavy harvest cut, which has left the site largely unoccupied by pine, will provide the opening for expansion of a latent crop of aspen sprouts or oak.

Treatment options.—Sites occupied by stands of this class are often better than average, with relatively deep soils and more mesic conditions. Conversion to pine is often a preferred option because of the high potential of the site. The oak or aspen competition must be reduced if planted pines are to regain control of the site.

Several factors must be considered in deciding whether to attempt conversion to pine. Expense of the conversion is high, often accompanied by undesirable esthetic disturbances. The condition of the aspen or oak must be considered in relation to its utility for other purposes. Some hardwood stands will be old and tall enough so that their usefulness as wildlife browse is negligible. Other stands will be younger sprouts of great importance to wildlife. Apart from their value as food and cover for wildlife, deciduous stands provide striking contrasts of autumn colors against the evergreens. Thus, esthetic considerations also enter into deliberations on type conversion.

If conversion to pine is the option chosen for whatever reasons, the existing pine trees will not adequately stock the site. Removal or deadening of the deciduous species and planting to pine is recommended. Choice of methods for site preparation must be left to the manager. Planting recommendations are found in the section on reforestation. Scattered pine trees are usually not abundant enough to be considered in the planting operation.

In the Bear Lodge Mountains and portions of the northern Black Hills, oak brush is an aggressive occupier of sites not continually dominated by pine. Once established, oak is difficult to eradicate. Consequently, unless oak brush is desired, extra care should be taken in timber sale prescriptions and logging operations to see that pines do not lose control of the site.

If the area chosen for timber production has adequate stocking of pines, but the pines are overtopped by aspen or oak brush, chemical treatment of the hardwoods seems the brightest prospect to permit pines to regain dominance of the site. Selective silvicides can be applied to the overstory without serious effects on the pine. If hardwood stems are relatively large and few in number, poisoning individual trees offers a good possibility for control. Mechanical control by plowing, bulldozing, or clearing around individual pines probably does not provide as effective a treatment as herbicides, and may be unsightly. Protecting the understory pines from mechanical damage is apt to be difficult and costly. Furthermore, mechanical treatments alone are unlikely to prevent hardwood reestablishment, and may even stimulate it.

Class 07; Aspen or Aspen-White Birch

Description.—This class contains no pine trees or at most only isolated individuals. Pure aspen stands may cover large acreages, generally occupying the more productive sites. The white or paper birch is usually a minor component in aspen-birch mixtures. The birch forms multiple stems or clumps by sprouting, and normally is confined to lower slopes, bottoms, and moist, cool sites.

Origin.—This class, like 06, most often develops as a result of major disturbance of an existing pine stand.

Treatment options.—More than one management goal may be considered with this class. Since wildlife habitat or scenic qualities may dictate maintenance of stands of this class (fig. 26), one option may be to do nothing at all. If pine culture is the goal, the aspen and birch will have to be eliminated or closely controlled, and pines seeded or planted.

Figure 26.—Picturesque aspen stand of poor technical quality, on an unfavorable site. Offsite character is common for aspen in the Black Hills.

Class 08; Pine Stand, Uneven-Aged

Description.—In nearly all cases, stands of this class have developed as a result of gradual invasion by pine into upland parks and abandoned fields. Typically, the stands are composed of several ages of pine progeny clustered around scattered parents. In later stages of the invasion process, clumps may merge to form more or less continuous stands of irregular structure. The openings into which the pines are expanding usually support grasses and forbs, with few shrubs or deciduous trees.

Origin.—Most of these stands are developing on an ecotone. They tend to wax and wane with cyclic changes in the climate and other environmental pressures. Prolonged protection from fire has evidently favored invasion by pine in many upland parks.

Treatment options.—In the few cases where pine culture is desired, site preparation and seeding or planting will restore the site to pine cover. Isolated seed parents should be harvested or killed first.

Because of the shortage of grasslands in the interior Black Hills, management strategy may call for park restoration for forage production. Where elimination of the invading pines is the objective, harvest of merchantable trees plus burning may be a good combination of treatments. Periodic burning may also be a good way to maintain pine-free parks. More needs to be learned about burning prescriptions, however, before the technique can be broadly recommended.

Class 09; Site Bare of Vegetation

Description.—These sites have been very recently devastated by fire. Both tree and ground cover have been burned. The fire was either so recent that vegetation has not had time to appear during the current growing season, or the fire occurred after one growing season but the following growing season has not yet begun.

Origin.—Fire.

Treatment options.—If the management objective is to return the area to pine production, seeding or planting can begin in the spring. The possibility of soil washing should be considered from two standpoints: method of reforestation, and need for soil stabilization during early phases of rehabilitation. Wagar and Myers (1958) found that seedings the first year after a burn in the Black Hills suffered the greatest losses from seed and soil washing. Severe erosion occurred on limestone soils with slopes as gentle as 12 percent, and on soils from metamorphic rocks on slopes of 20 percent or more. On the other hand, early establishment of tree cover is necessary because ground cover competition develops rapidly.

Class 10; Site Supporting Disturbance Cover of Grass, Forbs, or Brush

Description.—Pine cover is entirely lacking or represented by isolated individuals. No seed source is near enough to restock the area, or source is too scanty to effectively restock the area with an even-aged stand.

Origin.—Catastrophic elimination of an existing pine cover generally creates this class; fire, tornado, or insects are causal agents.

Treatment options.—Site quality will be a major consideration in deciding upon a treatment. If the productive capability is adequate and a return to pine cover is the management objective, site preparation followed by seeding or planting is indicated. If brush is well established, regeneration of a pine stand will be difficult. Contour plowing or bulldozing does not seem to adequately prepare heavy brush sites. Chemical treatments, developed in other areas

to control similar species, may be adapted to Black Hills conditions. Grass or forb ground cover does not present so much of an obstacle. Site preparation techniques commonly used in the Black Hills are effective.

Class 11; No Evidence of Previous Forest Cover

Description.—These are areas of permanent or semipermanent parks or meadows, with no evidence of stumps or standing trees. There are no remnants or pieces of charcoaled wood indicating earlier tree cover.

Origin.—No readily apparent reason for historical absence of tree cover. On bottom land stringers, sod competition and heavy livestock grazing probably do not allow pine seedlings to get started or become established.

Treatment options.—Few sizable, consolidated areas are found in this class. Much of the land is in private ownership. The need and benefits to be derived should be seriously considered before deciding upon afforestation. If afforestation is to be attempted, try a small-scale planting or seeding trial, first, using the best techniques currently known. If the trial produces good survival and establishment, then operational programs can be started.

REGENERATION CUTTINGS

Regeneration cuttings serve two purposes. First, they harvest crop stands that are mature according to management criteria and/or are due for removal as a silvicultural necessity. Second, they create conditions favorable for establishment of a new crop stand, usually by natural regeneration.

Because the several classic regeneration cutting methods are named for the manner in which the mature stand is removed, subsequent discussion will follow the usual custom and use the terms "harvest" and "harvest cutting" interchangeably with the terms "regeneration cutting(s)." Furthermore, in this Paper, the term "harvest" is reserved for a cutting or series of cuttings that results in the complete removal of a mature stand. It is not applied to intermediate, partial cuttings in immature stands, even though such cuttings may, in fact, yield a harvest of usable wood.

Guiding Principles

Final harvest is inevitable—no forest stand can be perpetuated forever. If not harvested by man, it will eventually be harvested by nature.

Final harvest is also the most drastic silvicultural treatment that can be prescribed, biologically and esthetically. Hence, the decision to harvest a stand should be based on a thorough analysis of management and silvicultural needs.

Choose a harvest method that is compatible with ponderosa pine's strong natural tendency, in the Black Hills, to form even-aged stands. In most harvest situations, the shelterwood method will be the best choice.

Where efficient production is a timber management goal, follow the rule: "only one crop of trees on the ground at a time, for as much of the rotation as is possible."

Background

Most of what is known about harvest cutting in the Black Hills has been learned by experience rather than research. Fortunately, the experience has been abundant, varied, and instructive.

During the mining boom—when there was a brisk demand for wood products of all sizes and shapes, and no harvest restrictions—clearcutting was the usual harvest method. Following establishment of the Forest Reserve and imposition of rudimentary harvest controls, a few large sales (including Case 1, see footnote 2) specified harvest of all timber, alive and dead, larger than a minimum diameter limit. Because this approach led to virtual clearing of sizable areas, most subsequent sale contracts for the next few years required retention of two or more seed trees on each cutover acre. This sort of harvest persisted until about 1908, when a two-cut shelterwood was adopted as standard practice.

Beginning in the mid-1920's, the shelterwood method was no longer recommended in National Forest marking guides; rather, individual-tree selection was favored. The main reason for this change, evidently, was to permit rapid coverage of large acreages of overmature timber urgently in need of silvicultural treatment to reduce risk and anticipated mortality. Use of the selection method continued until the mid-1950's, when revised guides once again acknowledged the suitability of even-aged management and prescribed shelterwood harvest. In initial form, the revised guides called for gradual removal of mature stands in three light cuts spaced 20 years apart, with retention of a few "insurance" trees above the replacement stand for an additional 20 years. On the ground, this conservative version of the shelterwood method was barely distinguishable from the individual-tree selec-

tion practice which it replaced. Within a decade, however, the guides again prescribed a two-cut shelterwood with timing of the removal cut contingent on underwood establishment and development. With this most recent change in practice, harvest experience on the Black Hills National Forest came full-circle back to where it started at the turn of the century (Newport 1956).

Lessons

Although the evolution of harvest practices in the Black Hills was largely a trial-and-error process, it entailed remarkably few errors. Only in rare instances have past harvest operations produced silviculturally damaging results. Most have been reasonably successful, as evidenced by the scarcity of poorly or non-stocked forest acres and the absence of any pronounced fall-down in growth or allowable cut during the old-growth liquidation period, now drawing to a close.

Perhaps the most important lesson to be learned from all this varied harvest experience is that, from the ecological standpoint, no high forest method can be considered wrong or wholly inapplicable in Black Hills ponderosa pine. Any one of the standard methods may be a silviculturally acceptable option under the proper circumstances. This does not mean, however, that all of the methods are equal in their range of applicability, probability of success, efficiency, and esthetic appeal.

Observations of the outcomes of many harvest operations, old and new, interpreted in the light of silvical knowledge, have led us to the following conclusions about the suitability of each of the four basic methods. The methods are ranked and discussed in order of decreasing usefulness.

Shelterwood Method

Experience indicates that this should be the primary regeneration method for Black Hills ponderosa pine. It is ideally suited and widely applicable. It capitalizes on the species' strong, natural tendency to form even-aged stands. Furthermore, it combines the advantages of continuous vegetative protection of the site; assurance of an adequate, well-dispersed seed supply; fair control over development of competitive ground cover; good control over accumulations of hazardous and unsightly logging residue; and an esthetically acceptable appearance, provided the harvest job is skillfully planned and executed.

The only important disadvantage is that the parent overwood will hamper development of the replacement stand if it is too dense or left in place too long.

A uniform, two-cut shelterwood is the most efficient and silviculturally acceptable variant of the method. The seed cut should be heavy enough to interrupt the competitive continuity of the mature stand and the removal cut should be timely.

A three-cut variant may be used in situations where the two-cut approach would create unusual problems of visual impact, residue build-up, risk of windthrow, or logging damage to reproduction.

Since the shelterwood method is recommended for general use in the Black Hills, additional details of its application are given in subsequent sections.

Seed-Tree Method

Many thousands of Black Hills forest acres have been harvested and regenerated successfully by this method. In a typical application, a heavy first cut removes the bulk of the volume in a mature stand—usually 90 percent or more—and leaves a light reserve stand to reseed the site. In medium to large sawtimber stands in the Black Hills, the seed-tree reserve will normally contain 5 to 10 trees per acre. This light residual stand is cut, or sometimes killed standing, after the replacement stand is firmly established.

The seed-tree method has one probable and two certain advantages, and at least three disadvantages, relative to the shelterwood.

On the plus side, a few widely spaced seed trees offer less interference to development of the replacement stand than a more heavily stocked, more competitive shelterwood. Also, final removal of a small number of seed trees will be less damaging to the new stand. Finally, because of its limited potential for seed production, a seed-tree stand is less likely to spawn excessively dense reproduction.

The method also has some disadvantages which deserve consideration. The heavy first cut will inevitably leave large amounts of residue on the ground. Accumulations may reach 20 tons per acre, dry, when more than 100 ft^2 of basal area is cut in a large sawtimber stand. Although this slash offers some protection to the site and developing seedlings, it represents a worrisome fire hazard and can be unsightly, even when carefully lopped and scattered.

Of all the methods, the seed-tree approach involves the highest risk of loss of seed source. Unless the few reserved trees have grown at a relatively wide spacing for several decades,

they will be vulnerable to windthrow or wind breakage after the protection of the surrounding stand is removed. Few, if any losses can be tolerated in a seed-tree stand, so leave trees must be chosen for windfirmness. Even then, their survival is a gamble on windswept sites.

The limited competition which favors development of pine seedlings under a seed-tree stand also favors development of other kinds of vegetation. Consequently, there is considerable danger of site capture by grasses, forbs, and brush unless a complete stand of reproduction becomes established promptly after the seed cut. Once a site is captured by other vegetation, pine regeneration becomes a slow and uncertain process. Even if tree seedlings manage to become established in heavy ground cover, their growth is apt to be hampered.

The seed-tree method is thus less appealing esthetically and more risky silviculturally than the shelterwood. However, it remains a legitimate harvest option which may be used to satisfy special management objectives.

Clearcut Method

This method removes a mature stand, or a portion thereof, in a single, clean cut. If the stand is to be regenerated naturally, either (1) the cut should be made during or shortly after the fall of a good crop of seed, or (2) the cutover area should be limited in size to permit adequate seed dispersal from the surrounding, uncut stand. In the Black Hills, where site quality restricts mature stand heights, adequate numbers of seeds cannot be expected to fly beyond about 2 chains on level ground. Hence, the maximum width of clearcut openings should be no more than 4 chains when there are seed-producing stands on both sides, and 2 chains when seeding will be from one side only.

Clearcuts can take the form of either blocks or strips. For improved appearance, openings should have irregular boundaries. Also, the long dimension of oblong blocks or strips should follow the contour, when situated on moderate to steep slopes.

Like the seed-tree method, clearcutting is an acceptable option from the silvicultural standpoint. Its best features are that it (1) entails little risk of loss of seed source, and (2) allows the replacement stand to develop free of both overhead competition and the threat of logging damage.

Its major disadvantages are that it generates maximum volumes of logging residues, and it affords little control over development of ground cover. Where large areas are cut over and regeneration depends heavily on seed dropped by the cut trees, the operation must be rated a long gamble. Odds of success can be improved by controlling seedeating rodents.

Despite its disadvantages, clearcutting will be the only appropriate method where natural stands are to be replaced by stands of genetically improved or introduced growing stock. In these cases, maximum size of clearing will not be limited by seed flight. Other management objectives, such as increased water yield and creation of wildlife openings, may also dictate some use of clearcutting in the Black Hills.

Selection Method

This method is designed to create and/or maintain uneven-aged stands. As a regeneration method, it is out-of-place in the naturally even-aged forests of the Black Hills—at least in regulated stands being managed for timber production. It can, however, be used effectively for late intermediate cuttings, of the sanitation salvage type, in mature or overmature stands which for some special reason cannot be harvested on schedule. Thus applied, selection cutting is simply a delaying tactic, aimed at maintaining the health and appearance and capturing the volume and value of a few high-risk trees in an overmature stand. Its use is not an alternative to eventual harvest and regeneration by one of the even-aged methods.

This kind of treatment might be appropriate in stands which are (1) especially scenic, (2) critically located near campgrounds or other recreation facilities, (3) temporarily inaccessible, (4) likely to gain bonus values if grown to larger size, or (5) scheduled for harvest during a period of low demand and prices for stumpage.

Selective removal of a few individual trees in a mature stand will not ordinarily promote establishment and development of much advance reproduction.

It has been suggested that the group-selection method might be used to convert even-aged stands of Black Hills pine into uneven-aged stands. This is silviculturally feasible, if one's definition of uneven-aged is broad enough to include a patchwork forest comprised of intermingled even-aged stands. A forest of this kind would simulate the natural structural arrangement resulting from the killing of patches of trees by bark beetles, fire, and wind.

The difficulty with this scheme is that conditions in the Black Hills are not conducive to the successful culture of the very small even-aged stands which characterize the group-selection forest. Even on the most productive sites, small trees do not develop satisfactorily under the

competitive influence of older, larger trees (fig. 27). Because of their elaborate root systems and extravagant demands for moisture, large trees can exert a suppressive influence over radial distances as great as 50 to 60 ft. Consequently, growth of reproduction is almost certain to be retarded over all or most of any opening less than an acre in size, if it is set in a matrix of mature trees. It is questionable whether a forest comprised of even-aged patches larger than an acre still qualifies as uneven-aged. Certainly, once the uneven-aged structure has been compromised to that degree, most of the advantages peculiar to the selection forest will have been lost.

The same conditions that restrain the culture of even-aged forests in the Black Hills summarily preclude culture of all-aged stands. Such stands, comprised of trees of many ages and sizes intimately mixed on each acre, are the cultural goal of harvest and regeneration by the single-tree selection method. Successful development and maintenance of this structural type requires (1) trees that are tolerant enough to grow at acceptable rates in proximity to others in superior crown positions, and (2) sites that are capable of supporting a deep canopy of moisture-dispersing foliage. These exacting requirements cannot be met by ponderosa pine on Black Hills sites, except in stands spaced widely enough to make all stand components free growing.

Figure 27.—Stunted 25-year-old seedlings struggling to survive in a small stand opening.

Shelterwood Method: Guides for Use

Because previous partial cuts have already produced regeneration in most mature pine stands in the Black Hills, opportunities to initiate shelterwood cuttings are currently quite limited. However, this situation will change in the next few decades as extensive stands that are now in the large pole and small sawtimber classes come due for harvest and regeneration.

The majority of these stands will be ideally structured and conditioned for regeneration by the shelterwood method. Most will have had two, three, or more intermediate cuts. They will be uniformly stocked with trees which have grown at moderate to wide spacings for several decades—vigorous trees with good crowns, stout stems, and proven resistance to windthrow. Most stands will contain 80 to 130 ft^2 of growing stock in trees averaging 14 to 18 inches d.b.h. Ground cover of herbs and shrubs, dominated by grass, will be present under stands at the lower end of the stocking range, but the cover will not ordinarily be dense enough to hinder pine regeneration. Advance pine reproduction, if present, will be sparse and nonvigorous.

Prescription for Seed Cut

If possible, mark the stand for treatment a few years before it is due for cutting, and arrange for flexibility in timing so that the logging can be done on demand, with about 1 year's advance notice. Specify logging during late summer and early fall.

Select and leave-mark 12 to 18 trees per acre. Aggregate basal area of leave trees should not exceed 35 ft^2 per acre. This restraint should pose no problem in most managed stands, since maximum d.b.h. at harvest is unlikely to exceed about 20 inches.

Select leave trees with special care. Insofar as possible, they should be superior trees:

- Dominants or codominants with long, full symmetrical crowns.
- Prolific cone producers, as evidenced by numerous shed cones at their bases.
- Phenotypically desirable with respect to growth rate, vigor, stem quality (form, straightness, branch size and angle), and freedom from insect and disease infestations.
- Uniformly distributed over the acres on which they occur. In cases where tree distribution forces a choice between leave tree quality and spacing, greater weight should be given to quality. However, avoid leaving trees in closely spaced pairs or groups.

Finally, prescribe a slash treatment that will result in a slash layer of minimum depth and maximum uniformity. Piling and burning, or chipping, may be justified for fire hazard reduction along the road, if it carries much traffic. Elsewhere, a lop and scatter treatment will suffice, if the lopping reduces the residue to short pieces and scattering is uniform.

Prescription for Removal Cut

The shelterwood should be removed completely as soon as a well-stocked replacement stand has become solidly established. Stocking in the new stand can be rated satisfactory when 80 percent or more of the mil-acres support at least one good pine seedling. Seedlings can be rated solidly established when they average 1 ft tall or taller. The removal cut can be made any time after the replacement stand meets these criteria. It should not be delayed beyond the time when most seedlings reach a height of about 3 ft (fig. 28).

The cut should remove all overstory trees with minimum damage to the replacement stand. Slash should be treated as prescribed for seed cut, but residue volume will be much less.

Basis for Prescriptions

The seed cut should be pre-marked and flexibly timed so that it can be made during the growing season just prior to maturation of a good to excellent seed crop. Such a crop can be forecast a year ahead from presence of first-year cones—visible through binoculars.

Late summer-early fall logging is best because it assures maximum disturbance of the seedbed just prior to seedfall. Disturbance breaks up the litter layer, exposes mineral soil, and uproots existing vegetation. Seed dispersal onto a freshly disturbed seedbed maximizes chances of getting a replacement stand started the first spring after logging. This, in turn, minimizes the regeneration period and gives the seedlings a competitive advantage over developing ground cover.

Stocking is relatively critical in the shelterwood stand left by the seed cut. Enough wind-firm trees should be retained to (1) assure uniform dispersal of adequate numbers of seeds over the entire area to be regenerated, and (2) provide some protection to the site and some impediment to development of ground cover. At the same time, stand density should be low enough to inhibit excessively dense reproduction and permit reasonably rapid development of the new stand for the first several years after its establishment.

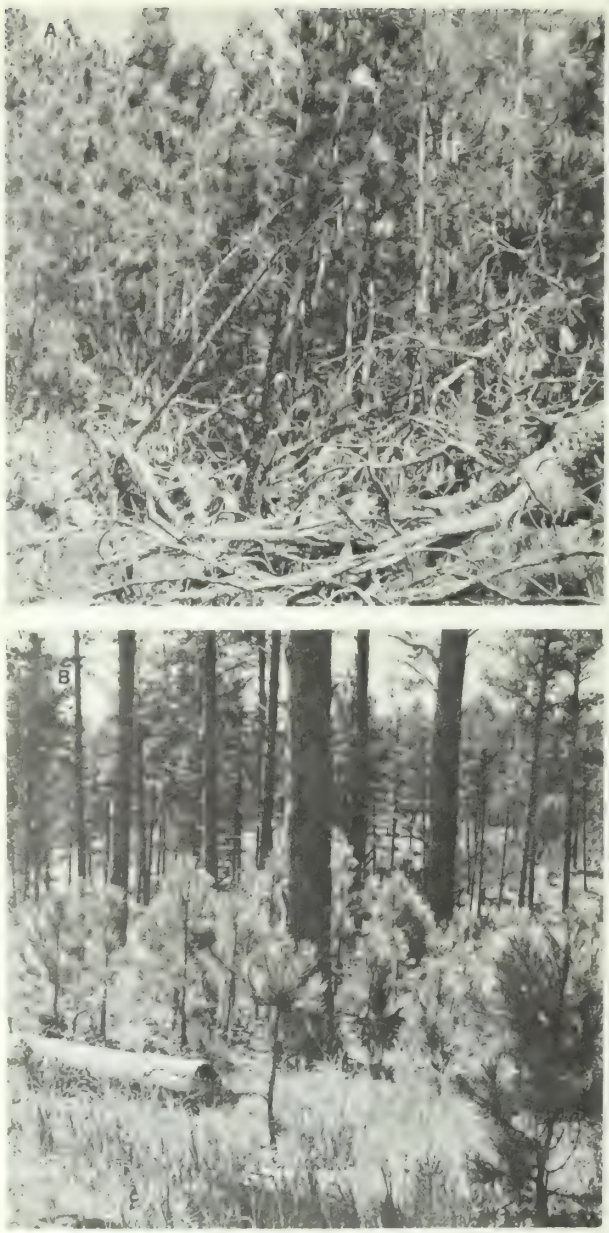

Figure 28.—*A,* Sawtimber harvest in dense stands of overgrown reproduction is difficult, damaging, and unsightly. Here, overwood should have been removed 15 to 20 years earlier. *B,* Shelterwood with 10-year-old reproduction below; ready for overwood removal.

Stocking and seed supply.—We have no reliable, direct evidence of how many parent trees must be reserved in a shelterwood to assure uniform dispersal of enough seed to establish a well-stocked new stand. However, there is some indirect evidence that will support a general estimate.

First, how much seed is needed to restock an acre of reasonably hospitable forest site? A probable indication can be found in Wagar and Myers' (1958) evaluation of factors influencing success of direct seeding of ponderosa pine in the Black Hills. Based on results in some 150 seeding operations, they concluded, that, under generally favorable conditions, 4 to 6 pounds of broadcast-sown pine seed per acre is as likely to produce a satisfactorily stocked seedling stand as any larger amount, up to 16 pounds. Four to six pounds is about 48,000 to 72,000 seeds.

If a one-shot, artificial sowing of that amount of seed is normally enough to restock a deforested acre, it seems reasonable that a like amount, sown naturally on a freshly cutover acre, would also be apt to produce the desired results. It seems especially reasonable in view of the backup feature of periodic natural seeding.

How many shelterwood trees must be retained on an acre to disseminate 48,000 to 72,000 seeds in a good crop year? The only relevant local study was made by Carlos Bates in a single "moderately stocked" mature stand near Custer, during the 14-year period 1912-25.[6] He made annual, direct determinations of cone and seed numbers and seed viability by collecting all cones from felled sample trees. Bates' data revealed that (1) good to excellent cone crops occurred in 5 of the 14 years, with an average frequency of 3 years; (2) few, if any, cones were produced in the other 9 years; (3) dominant and codominant trees were consistently the heaviest cone producers; and (4) average yield per tree for these best producers in the best crop years was 125 cones, containing 4,100 seeds, of which about 50 percent were viable.

The data suggest that 12 to 18 trees per acre should suffice to supply adequate seed for regeneration in a good crop year. It is possible, of course, that the single stand studied by Bates was not typical in terms of amount and/or quality of seed produced. Even so, the risk of an inadequate supply seems to be minimal, because the prescribed number of trees is based on an assumption of full satisfaction of expected seed requirements in a single year, with no allowance for subsequent reseeding.

If the 12 or more trees are distributed over an acre with fair uniformity, no tree should be much more than 1 chain distant from its neighbors. Consequently, all points within the acre should be within easy flight distance from ponderosa pine seed.

[6]*Unpublished data on file at Rocky Mountain Forest and Range Experiment Station, Rapid City, South Dakota.*

Stocking and competition.—A stand of 12 to 18 mature trees per acre will probably provide an acceptable compromise between wanted competition for control of ground cover and unwanted excessive competition that would seriously retard development of the young replacement stand. If grown at spacings conducive to good crown development, such a stand can be expected to provide a crown canopy density within the range of 15 to 25 percent.

Any mature stand which has been sufficiently well stocked to exclude advance pine reproduction will have a sparse, nonvigorous ground cover below it. Most of the plants persisting will be shade tolerants not likely to benefit much from sudden, drastic exposure. Thus, the problem of herbaceous competition will be minimal immediately after the seed cut is made. Obviously, the replacement stand should be established as soon as possible, while this favorable situation still prevails.

Once a heavy seed cut is made, as prescribed here, invader-type ground cover—mostly grasses and forbs—will move in rapidly to capture the site. If pine regeneration is delayed, the speed and success of the regeneration process will depend heavily on the degree to which overwood competition controls ground cover density, vigor, and growth.

What about the impact of overwood competition on the pine seedlings themselves? Observations indicate that seedlings can establish themselves readily and grow satisfactorily for several years under a freshly cut, uniformly spaced parent stand containing less than 40 ft^2 of basal area per acre. Tolerance of young Black Hills ponderosa pine is great enough that light shading poses no problem. Competition for moisture, on the other hand, may be critical in some years. It will be least limiting, however, during the first few years after the seed cut—prior to extension of parent-tree root systems into growing space vacated by cut trees.

INTERMEDIATE CUTTINGS IN MANAGED STANDS

A managed timber stand implies that goals have been established by management decision, plans have been made for goal attainment, and some action has been taken to implement these plans. Effective action will necessarily include some level of silvicultural **control** over (1) growth and development of the stand and its components, (2) intermediate and final harvest yields, and (3) the technical character, or quality, of the material removed and retained during each stand entry.

In the Black Hills, as elsewhere, the silviculturist's most powerful tool for controlling growth, yield, and quality of managed stands is the manipulation of amount and kind of growing stock and its distribution on the site. Manipulation takes form of repeated intermediate cuttings, usually of the type technically classified as thinnings (fig. 29). Other types of intermediate cuts, such as cleanings or weedings, are infrequently needed in the Black Hills because most stands are essentially pure ponderosa pine.

Guiding Principles

In **every** thinning, select leave trees primarily on the basis of vigor, health, growth rate, and stem quality. Their growth potential and character will determine the value of the final crop. Retain the best growing stock in every intermediate cut. Do not overemphasize uniform spacing, but avoid leaving close pairs of trees or tight clumps.

Thin and rethin each stand before any serious, general decline in tree growth and vigor due to excessive intrastand competition. Make precommercial thinnings in dense, young stands as soon as possible after trees are solidly established—preferably by or before the time they reach breast height. The problems of excessive slash and risk of loss of reserved trees become steadily more troublesome with increasing tree size.

Figure 29.—Thinning is the silviculturist's most powerful tool for controlling growth, yield, and quality.

Thin stands primarily from below. Concentrate most of the cut on poor competitors of small size and low vigor, but also remove poor-quality trees from the upper crown classes.

Be sure that prescriptions for reserve stocking and thinning frequency are consistent with management goals for timber production **and** associated uses. Tailor prescriptions to specific stand and site conditions. Allow for a reasonably well-balanced distribution of stand size classes in a regulated forest.

Watch for opportunities to use differential thinning intensities to consolidate neighboring small stands of nonuniform average diameter into larger, uniform stands of manageable size. Or, conversely, break up undesirably large blocks of uniform stands into small, nonuniform stands.

Be conservative in prescribing initial thinnings in stands which have been excessively dense for long periods. Do not open such stands too much, too fast. Allow for probable losses to windthrow and snowbreak.

Thinning Options

No thinning is intrinsically good or bad. It can be rated qualitatively only on the basis of its value as a means of implementing some well-defined management strategy. Hence, a good defensible thinning prescription must be based on decisive answers to these four questions:

- Will this stand (or class of stands) require thinning in order to satisfy management goals? If so:
- What kind or kinds of thinning?
- When?
- How much growing stock should be removed and retained?

Answering these questions assures consideration of the full array of thinning options: To thin or not to thin, method, timing, and severity. All of these are interdependent, but the relationship between timing and severity is an especially close one.

Thinning Versus No Thinning

To arrive at a sound decision on whether or not to thin a given stand, the silviculturist

should first consider the objectives established for that particular stand or the class to which it belongs. Management strategy may selectively exclude some stands from a thinning program to satisfy goals for other than wood production. For example, stands on unproductive sites may be left untreated, together with some stands needed for escape cover for game, special scenic effects, barriers, screening, and other purposes. Conversely, management may decide that intermediate cuts should be made in some stands to meet wood production commitments, to enhance browse or water production, or for a variety of esthetic reasons.

In the more common cases where the choice of thinning versus no thinning is left to the silviculturist, he should determine whether there is a need and justification for the treatment. In most naturally regenerated pine stands in the Black Hills the need for thinning is likely to develop early and recur periodically. Hence, a decision on desirability of thinning will often be made easily, at least where wood production is a primary management goal.

Thinning Method

The choice of a thinning method will depend on the present structure of the stand and the structural changes needed to advance it at an acceptable rate toward final harvest goals. In most previously unthinned stands, the best initial treatment may be a combination of a light to moderate crown thinning and a moderate low thinning. Ordinarily, subsequent rethinnings should be of the latter type. One possible exception might be an unregulated forest where an unbalanced distribution of stand sizes requires temporary maintenance or reduction of average d.b.h. in stands of some classes. Another exception might be where the silviculturist decides, in the interest of management efficiency, to meld two or more small stands of dissimilar development into a single, uniform stand of larger area. In either of these exceptional situations, crown thinnings might be used.

Timing

The silviculturist's options on timing are to thin now, later, or both—as in the case of preplanned thinning schedule. Urgency of the need for thinning will be an important factor. Criteria to consider in assessing urgency include health, vigor, susceptibility to damaging agents, and growth rates of the best elements of the growing stock. The decision on timing will probably also be strongly influenced by underlying management strategy, particularly as it pertains to intermediate and final product goals, rotation length, stage of stand development, stemwood merchantability standards, markets, and management willingness to invest funds in precommercial thinnings.

Timing of treatment will also depend heavily upon severity of and, to a lesser extent, the method used in previous thinnings. As a general rule, the effectiveness of a series of thinnings will be enhanced by timely rethinnings, made while the trees are still actively responding to the preceding density adjustment.

Severity

Factors to be considered in deciding how severe a given thinning should be include: (1) amount of excess growing present in relation to an ideal for any given stage of stand development; (2) the prospect of a subsequent thinning and the probable return time; (3) risk of damage to the stand and/or site; (4) risk of excessive accumulations of thinning residues; (5) minimum salable wood yield per unit area for commercial thinnings; and (6) management goals or desires unrelated to wood production.

OTHER CULTURAL TREATMENTS

In addition to thinning, the Black Hills silviculturist has two other cultural treatment options which he may exercise to influence growth, yield, and quality. First, he may use artificial pruning to increase production of knot-free stemwood, reduce incidence and impact of western red rot, and, possibly, to modify stem form. Second, he may decide on artificial rather than natural regeneration to restock harvested or otherwise deforested acres, using improved strains of ponderosa pine or trees of other species, native or exotic.

Unfortunately, as with application of supplemental water or nutrients, the value of these practices remains unknown in the Black Hills. The biological and technical desirability of pruning some of the best trees on good sites is fairly well accepted, but the economic desirability of the practice remains to be demonstrated. Even less is known about the potential value of new or improved growing stock to replace natural stands. Furthermore, no seed or stock of predictable adaptability and performance is currently available for use here.

REFORESTATION OF PINE SITES

Principles

Ponderosa pine is the predominant overstory vegetation on most Black Hills sites. It grows so extensively throughout this region that almost any site on which artificial regeneration is contemplated formerly has supported pine. Three notable exceptions to the nearly complete pine cover are the Reynolds and Gillette Prairies and the Bald Hills, all located in the central Black Hills.

Because of the favorable climatic factors that assist natural regeneration successes, artificial regeneration, too, can normally be expected to succeed. Both seeding and planting are common regeneration practices in the Black Hills. Seeding has received only intermittent attention, while planting has gained solid acceptance. Both techniques, however, have been employed here since at least the early 1900's. Success has been evaluated primarily through empirical trials, though a limited number of research studies have been conducted.

Planting often produces a better success ratio than seeding, though Wagar and Myers (1958) identified some of the factors affecting results of direct seeding.

Artificial regeneration of pine stands is now largely confined to areas recently devastated by fires, tornadoes, or other catastrophies. Most of the large, old burns have already been reforested as completely as is practical. Costs of reforestation and unsatisfactory growth rates ordinarily preclude regeneration of sites with indexes less than 50, unless esthetics, wildlife habitat, or stabilization of soil are primary objectives.

Choice of either planting or seeding depends on a number of factors. Two points about direct seeding, however, must be kept in mind: (1) while per-acre costs are often less than half of those for planting, a second seeding—in case the first is not successful—will be more expensive because the benefits of a site preparation job fade rapidly; and (2) with the exception of limited areas of rocky sites, one should not attempt to direct seed any site that would be unsuitable for planting—at least, for purposes of timber production.

Site Preparation

Experience has shown that wherever ground cover of grass, forbs, or shrubs has become established on potential planting or seeding sites, preparation of those sites is essential. Hardwood overstory must also be reduced or eliminated on sites to be reforested by pines.

Mechanical or chemical methods can be used, either singly or in combination. Although no local research has been conducted to evaluate their relative merits and effectiveness under Black Hills conditions, much has been learned about mechanical methods through experience.

Mechanical

Crawler-type tractors, pulling disc-plow attachments, effectively uproot small trees and plow contour furrows through established ground cover. One of the plus features of such plowing is that the furrows will catch and concentrate surface water runoff. An obvious disadvantage is that virtually the entire "A" soil horizon may be removed, which is especially undesirable where soils are shallow. Furthermore, critical moisture may be evaporated through the exposed soil. Sometimes the furrow forms a water channel, and a number of seeds can be washed along in the stream, collecting in small settling basins.

It is usually necessary to fence out livestock for a few years from sites that have been prepared with contour furrows. The furrows are favored by livestock as pathways, and many seeds or seedlings are trampled.

Chemical

Herbicides offer promise both to control ground cover and to eliminate tree and shrub overstory.

Heidmann (1967) found a rate of 5 pounds of dalapon per acre killed 86 to 94 percent of the two grasses to which it was applied. Cost per acre in this Arizona trial was only $6.78. Herbicide treatment has the advantage of leaving the "A" horizon undisturbed, while the dead ground vegetation serves as a mulch to conserve soil moisture (Heidmann 1969). Repeated annual treatments may interfere with normal growth and development of the trees, however.

There is some uncertainty about the use of herbicides because of concern over dangers to the environment. Many can still be used, and the search continues for new formulations that will be more effective, more selective, and safer. Any herbicide use should be preceded by a careful study of suitable types and their possible effects on the local environment. Refer to the pesticide precaution statement on the inside back cover.

Planting

Stock should be grown from seed collected from as close to the site to be planted as possible. Presently, seed identified simply as coming from the Black Hills is used for reforestation throughout the Black Hills and Bear Lodge Mountains. Research now underway will indicate whether more specific matching of seed collection to planting site is advantageous.

During years of favorable moisture, 2-0 root-pruned planting stock may be expected to provide the best combination of ease of planting, economy, and performance (Boldt 1968). Conclusive evidence about performance of this and other classes, such as 1-0, 1-1, and 2-1, during years of unfavorable moisture is lacking, but the best choice appears to be 2-0.

Recommendations concerning seedling size and quality for the Southwest (Schubert et al. 1969) appear to be valid for the Black Hills as well. They suggest using seedlings with a vigorous top of 4 to 6 inches, root-collar diameter of at least 0.16 inch, and a well-developed root system of 8 to 10 inches (fig. 30). Grading to a standard such as this may be expected to pay large dividends in seedling survival.

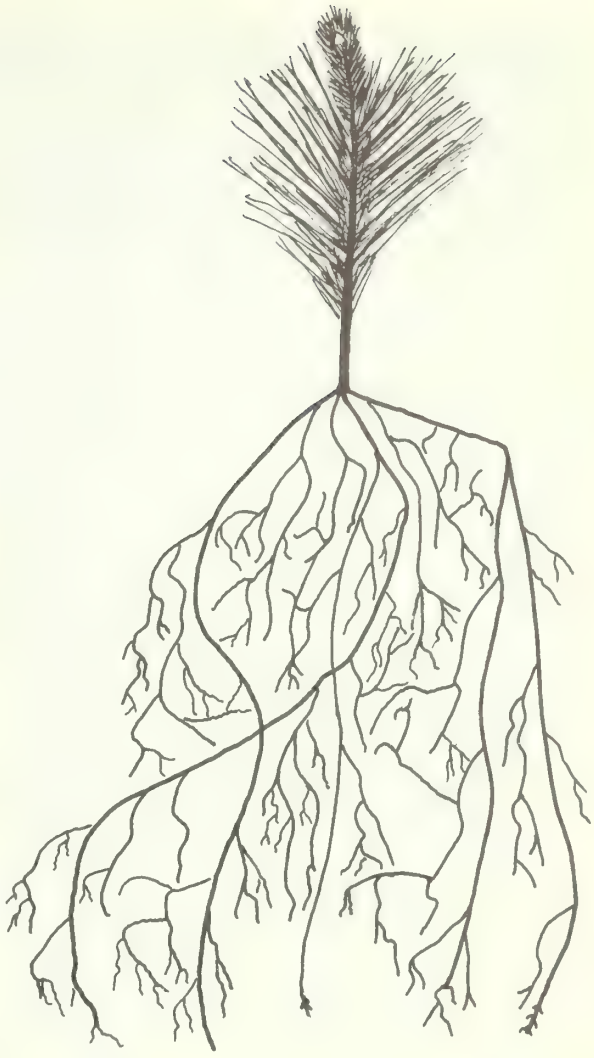

Figure 30.—High quality planting stock that should yield large dividends in seedling survival and growth.

Hand Planting

Some sites too rough or precipitous for machine planting, although of high enough quality to warrant reforestation, must be planted by hand. A mattock that will dig a hole large enough to accommodate the seedling's root system, without doubling back the ends of the roots, is the best tool to use. One cannot emphasize too strongly the need to plant high-quality, healthy trees carefully and properly. Failure to make good contact between mineral soil and roots, or planting seedlings whose roots have dried out, will ordinarily negate the time and money spent in planting them. First-year seedling survival of more than 90 percent can be attained by careful planting of well-cared-for stock (fig. 31).

Machine Planting

Planters that are attached to crawler-type tractors can be successfully used in the Black Hills, and will accommodate the same seedling sizes that are used for hand planting. Precautions to be observed in machine planting are much the same, regardless of where the plantings are made. Schubert et al. (1969) summarized them as follows:

- Planting depth—adjust coulter and trencher so trees can be placed at correct depth with roots fully extended.
- Pack soil—adjust packing wheels so soil is pressed firmly around roots.
- Trees in hand—remove no more than 10 to 15 trees from tray at any one time.
- Trees in tray—keep roots moist at all times.

Spacing Guides

Site preparation by contour furrowing imposes some restrictions on spacing, because the

Figure 31.—Careful planting on a well-prepared site is usually successful in the Black Hills.

furrows can seldom be plowed closer than about 10 ft apart. Distance between trees within the furrow should not be closer than about 8 ft. A spacing of 8 by 10 ft yields roughly 540 trees per acre.

If some other technique of site preparation is used—such as chemical treatment—the silviculturist will have more freedom in choosing spacing and number of trees per acre. The goal, however, should be reasonably full-site occupancy by trees. From 500 to 800 seedlings per acre is a reasonable number to plant on moist sites.

There is no economic advantage to complete site occupancy by trees at plantation establishment, even where wood production is the primary goal. Where the ultimate objective is timber production, however, some sites may require nearly full stocking at the outset as a defensive measure against excessive competition from undesirable trees or other shrubby vegetation.

Seeding

Seed Collection

Insofar as possible, seeds should be collected from trees that exhibit desirable traits of growth, form, and resistance to pests. Ideally, trees to be favored in silvicultural treatments, and trees from which seed is collected, should have the following characteristics:

1. **Growth rate:**
   - Height—should equal or exceed index curve values for the site at tree age.
   - Diameter—average 2.0 inches or more per decade.
2. **Age:** 75-150 years (for seed collections only).
3. **Stem:** Straight, without forks or excessive taper.
4. **Branches:**
   - Small in diameter.
   - Short in length.
   - Horizontal in projection from bole.
   - Average four or less per whorl.
   - Live crown 40 to 60 percent of total tree height.
   - Nonpersistent after death.
5. **Bark:** If candidate has black bark, wide fissures should show bright orange color, indicating vigorous growth.
6. **General health and vigor:** Candidate should show no evidence of successful attack by insects, diseases, or porcupines; should have dark green needles; should show evidence of good cone production in the past (old cones on the ground).

Hopefully, most of the local requirements for pine seed during the next decade will be met by collections from a seed production area recently established by the Black Hills National Forest near the Buskala Burn in the northern Hills. Successive thinnings in this 40-acre tract will be aimed at leaving only the best trees for growth, quality, and seed production. Best quality seed is obtained by collecting cones directly from the trees rather than from squirrel caches.

Seed Treatment

Present practice on the Black Hills National Forest is to ship green or partially open cones to the Mount Sopris Nursery in Colorado for extraction, treatment, and storage.

Seed treatment for field sowing normally includes application of a fungicide, rodenticide, and bird repellent. New formulations for seed

treatment chemicals, as well as chemicals for all purposes, are continually being developed. Some potent and persistent chemicals are occasionally withdrawn from accepted usage. It is not practical, therefore, to recommend prescribed dosages of specific chemicals where the research and development field is so dynamic. Again, consultation with specialists and regulatory agencies for up-to-date recommendations and registrations is necessary.

Sowing Techniques

A number of devices and techniques have been used or considered in the Black Hills, but none have been evaluated by research. Site preparation, which is necessary to reforest most Black Hills sites, limits the techniques that can be used. A system that will place one seed per unit distance in the furrow or one seed per place in prepared spots is the most satisfactory. Multiple placement of seeds does not work well because climatic factors favor germination and survival of all seedlings, while natural competition does not "thin out" multitree spots. Broadcast seedings have been successful (fig. 32).

Seeds should not be deeply covered by soil. A sowing depth equal to the diameter of the seed is satisfactory. Some soil covering over the seed offers physical protection, both from rodent depredations and from inclement weather. Too great a depth of sowing will either prevent germination or limit the number of seedlings which emerge through the ground surface.

Figure 32.—A highly successful broadcast seeding in 1941 on a 2-year-old burn resulted in this stand in 1957.

NEEDS FOR ADDITIONAL RESEARCH

Because of rapidly mounting pressures from an assortment of forest resource uses, the day has past when silviculture in the Black Hills can be aimed solely or even primarily at improved timber production. As this Paper shows, much has been learned about timber-oriented, single-purpose silviculture. This knowledge is valuable, but no longer sufficient. Instead, the challenge for research, now, is to develop a much wider range of cultural options so that silvicultural practices can simultaneously serve the needs of various combinations of integrated forest uses.

As a prerequisite to further work on prediction of responses to cultural treatments, both of trees and associated vegetation, we need to develop a better method for rating site productivity. The currently used method—site index based on tree height and age—has not proven a satisfactorily sensitive indicator of differences in site productivity. Its limitations are evident in the remarkable variations in periodic volume production observed among stands of similar age, size, and stocking on sites with similar indexes. Ideally, the new method should be only partially dependent upon, or independent of, existing vegetation. It should enable resource managers to rate the productive capacities of forest sites precisely and directly, using soil and other environmental factors as determinants. Resultant productivity ratings should be applicable to subordinate vegetation as well as trees.

We need to develop a refined model of the forest production system, capable of simulating the behavior of the intensively cultured stands of the future. To be most useful to forest managers, the simulator should forecast both the biologic and economic consequences of various kinds and levels of cultural activity throughout a rotation. It should be able to accurately predict the growth, structural development, and yields of stands maintained under various cultural regimes, thus enabling managers to select those regimes which produce outcomes most closely matching management goals. Projected yields should reflect multiple product potentials and be qualified by statements of statistical confidence. Finally, the model should be adaptable to the larger, more complex problem of simulating mixed vegetative production for entire plant communities under management.

We need to continue our search for superior strains of forest trees. The goal should be to develop breeding stock of proven superiority, for propagation to upgrade forest productivity and quality. The search should be focused primarily on ponderosa pine, both from local and nonlocal provenances. Criteria of superiority should include growth efficiency, stemwood quality and value, and resistance to pests and environmental stresses. Secondarily, we should also search for outstanding strains of other, non-native tree species which are adapted to the Black Hills environment and might be suitable for enriching the composition of our largely monotypic forest.

Other important, but less urgent problems needing research study are:

- Refinement of regeneration cutting practices to provide better control over speed of establishment and initial stocking in reproduction stands.
- Relation between growth rates of trees and the technical properties and value of their stemwood.
- Relations between soil moisture, stocking, and growth in cultured stands.
- Silvicultural uses of prescribed burning.
- Potential effectiveness of silvicultural practices for indirect control of bark beetles.

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☆ U.S. GOVERNMENT PRINTING OFFICE: 1974 — 678-255 / 25 REGION NO. 8

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1974. Silviculture of ponderosa pine in the Black Hills: The status of our knowledge. USDA For. Serv. Res. Pap. RM-124, 45 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

This Paper, intended as a guide for professional foresters, describes major silvicultural conditions likely to be encountered in the Black Hills, reasonable treatment options, and probable results and implications of these treatments. It also describes silvical characteristics and behavior of Black Hills ponderosa pine, and a variety of proven silvicultural tools.

Oxford: 181$174:187. **Keywords:** Timber management, silviculture systems, Black Hills ecology, *Pinus ponderosa.*

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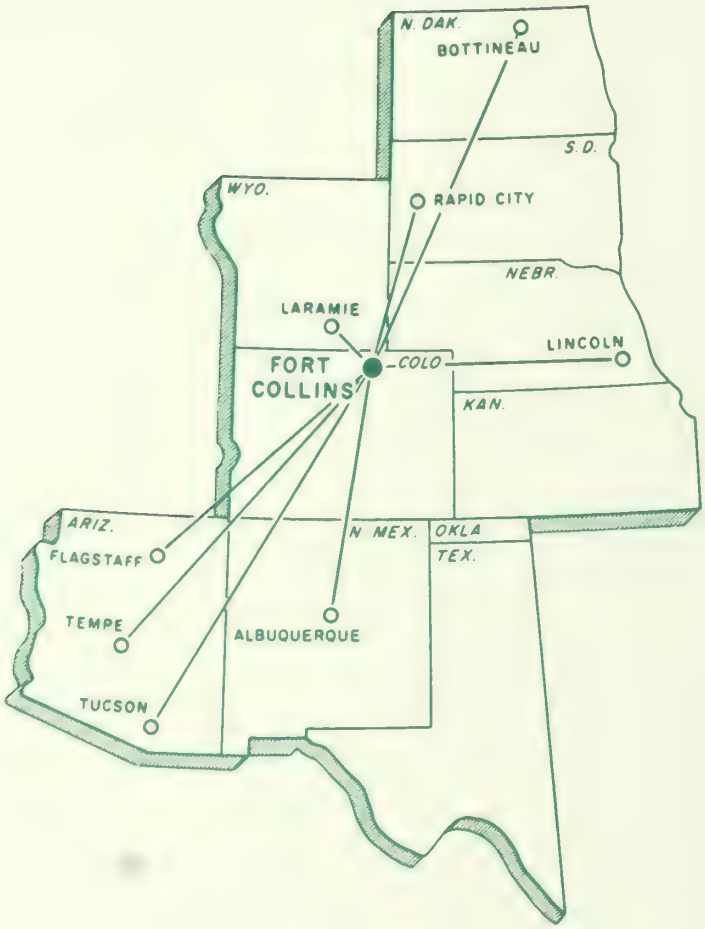
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DEMONSTRATION TEST OF INWOODS PULP CHIP PRODUCTION IN THE FOUR CORNERS REGION

George R. Sampson, Harold E. Worth, and Dennis M. Donnelly

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Abstract

Pulpwood and nonmerchantable material were chipped in the woods by a portable debarker-chipper. Two test areas were harvested: a ponderosa pine site in Arizona and a spruce-fir site in Colorado. At the pine site, both saw logs and pulpwood were harvested; saw logs were trucked to a sawmill, but sawtimber tops and pulpwood trees were debarked and chipped in the woods. Harvesting at the spruce-fir site was a thinning of pulpwood-size material following a sawtimber harvest. Sound dead timber was chipped along with thinnings. Chips from both areas were delivered to a pulpmill at Snowflake, Arizona. Feasibility analysis included physical, economic, and environmental evaluation of the inwoods debarking-chipping system as compared with conventional roundwood harvesting.

Oxford: 66:67:311:861.0. **Keywords:** Chipping machines, pulp chips, pulpwood logs, logging economics, logging operations.

Trade and company names are used for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.

USDA Forest Service
Research Paper RM-125

July 1974

Demonstration Test of Inwoods Pulp Chip Production in the Four Corners Region

by

George R. Sampson, Market Analyst
Harold E. Worth, Principal Wood Technologist
and
Dennis M. Donnelly, Associate Systems Analyst
Rocky Mountain Forest and Range Experiment Station[1]

[1] *Central headquarters maintained at Fort Collins in cooperation with Colorado State University.*

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FOREWORD

The study reported here was supported in part as a Demonstration Project of the Four Corners Regional Commission, under their Technical Assistance Grant FCRC No. 132-301-014. The Rocky Mountain Forest and Range Experiment Station, USDA, Forest Service, coordinated the study. Southwest Forest Industries, Inc. was a major cooperator, providing the support functions of falling, skidding and chip hauling. Other cooperators were the Southwest and Rocky Mountain Regions and Forest Products Laboratory of the USDA Forest Service, and the University of Arizona.

We express appreciation to the Four Corners Regional Commission for their financial assistance and particularly to Carl A. Larson, Chief Program Administrator, and to Dwight Neill, Colorado Governor's Alternate on the Commission, for the active interest they took in the study and the help they gave in formulating the plans. The authors are also particularly appreciative of the fine spirit of cooperation that existed among all of the participants and for the very substantial financial and manpower contributions made by Southwest Forest Industries, Inc. and our colleagues in the Forest Service.

Demonstration Test of Inwoods Pulp Chip Production in the Four Corners Region

George R. Sampson, Harold E. Worth, and Dennis M. Donnelly

SUMMARY AND CONCLUSIONS

During the summer of 1973, Southwest Forest Industries, Inc., cooperated with the Forest Service, USDA, in a study of inwoods production of pulp chips. The purpose was to find a feasible means of producing pulp chips from small trees and from residues ordinarily left in the woods after harvest. In this demonstration test, partially funded by the Four Corners Regional Commission and involving several other participants, a Nicholson Logger Model Utilizer debarked and chipped pulpwood, commercial thinnings, and associated nonmerchantable timber (fig. 1). Other harvesting functions were performed using conventional falling and ground skidding practices. Chips were transported from the forest chipping sites to the pulp mill or reload stations by highway-type chip vans.

The inwoods demonstration tests were conducted at two locations — one in ponderosa pine timber near Springerville, Arizona, on the Apache National Forest where pulpwood trees and sawtimber tops were chipped, the other in the spruce-fir type near Rico, Colorado, on the San Juan National Forest where thinnings and standing and down dead timber were chipped. The study spanned 63 working days from mid-June to mid-September, during which approximately 1,140 tons of pulp chips (bone-dry basis) were produced.

Operating conditions, times required for each harvesting function, delays and their causes, and production data were subsequently analyzed to estimate productivity and unit costs. Comparisons were made between this system and conventional means of producing pulp chips.

Conclusions reached include the following:

1. Demonstrations in Arizona and Colorado showed that the system works.

Formal demonstrations arranged on each of the test areas proved that there is considerable local interest in inwoods production of pulp chips. About 130 representatives of industry, public agencies, the press, universities, and the general public went to considerable trouble to get to the remote test areas for the demonstrations. While prospective entrepreneurs that observed the operation were not immediately convinced of its local applicability, most are actively interested in the system and have reserved judgment until the results of this analysis are available.

2. No major physical limitations were found.

The pulp chips produced were of high quality. Physical limitations of the system center around operating efficiency and the resultant costs. The system required more log handling than expected, and more than is needed in conventional harvesting. Also, the debarker-chipper was inoperable due to breakdowns an inordinately high proportion of the time. Some of this was attributable to power plant problems associated with high altitude operation. Design changes to correct power problems and the avoidance of jamups would likely remedy much of this limitation.

Fig. 1. — The Nicholson Logger Model Utilizer in action.

Moving and positioning the debarker-chipper and chip vans on roads and terrain typical of conventional harvesting conditions did not pose any insoluble physical limitations. However, the debarker-chipper and chip vans are somewhat more sensitive to adverse weather which results in unfavorable ground and road conditions than are conventional log loading and hauling equipment.

3. Economic feasibility depends on operating efficiency.

Unit costs of producing chips were substantially higher with this system of inwoods chipping, as it actually performed in these tests, than for conventional means of production. If the productivity of the debarker-chipper unit could be improved for Southwestern altitude, weather, and road conditions through design changes and increased operating efficiency, unit costs could possibly be reduced sufficiently to compare favorably with conventional alternatives. Improvements required would include increasing the time in actual production of chips to approach 80 percent of the available operating time, and substantially reducing chipper moving time. This level of productivity appears to be within reach if the machine can be successfully redesigned for reliable high altitude operation and better maneuverability. It would also be necessary for the crew to become better organized and more expert in operating the system.

Although chip production costs are high, opportunities for reduction are apparent if mechanical and logistic difficulties experienced in this short-term test could be resolved in an ongoing operation. It is also apparent that the costs of obtaining chips from other sources are rising as a lesser proportion of the demand can be supplied from mill residues and pulpwood locations nearer the pulp mill. Comparison of inwoods chip production costs with present chip costs may therefore not be appropriate for future operations.

Timber utilization was improved over conventional logging as a result of inwoods chipping. This improvement was much greater in the spruce-fir type than in ponderosa pine. However, most of this same improvement is already being attained in some operations through removal of nonmerchantable timber in conjunction with regular timber harvests. While this latter approach would tend to result in somewhat lower total volumes removed than inwoods chipping, due to the high cost of hauling and handling cull material, it offers an opportunity to make better product sorts of both merchantable and nonmerchantable material at a mill yard and therefore can yield higher product values.

4. A substantial log deck is required.

The scope of this test did not permit evaluation of all possible operating modes. It was therefore necessary to subjectively select which modes would be tested, and then to project from the data obtained any variation in performance from the modes tested.

Conventional falling and skidding systems were found to integrate well with inwoods chipping, but considerable reskidding was required to build deck sizes up to practicable levels for each setting of the debarker-chipper. Any changes to improve the efficiency of these functions would be based on the same considerations as for regular pulpwood or sawtimber harvests.

Bucking practices were adjusted as needed to provide chippable material plus any other products to be harvested. For multiproduct areas, saw log tops were bucked off at the stump but were skidded and decked along with saw logs and pulpwood. Tops were limbed predominantly at the stump, with some cleanup at the landing. Log bucking and sorting under these conditions present the same problems as in conventional logging, and it is to be expected that some merchantable saw logs will end up being chipped. Most pulpwood-size material and chippable cull were limbed at the stump and skidded full length. To obtain the greatest efficiency in chipping it is important to leave logs and pieces as long as possible. Only when the log has severe crook is it desirable to buck it into a shorter length. It is also occasionally desirable to buck off a butt swell on a piece that would otherwise be too large for the debarker.

Variables affecting operating efficiency of the Utilizer include log inventory at the machine, size and type of landing, materials handling and maintenance at the machine, and procedures for moving the machine from landing to landing.

- Maintaining an inventory of chippable wood at the machine at all times is critical to the economics of the operation. Because delays in chipping for lack of logs are costly, a substantial cold deck is required at the machine. Considerable reskidding was required to build decks to adequate size. Hot logging to the machine under the conditions surrounding these tests was not feasible.

- The size and type of landing required for chipping depend on terrain, road system development, and the availability of natural openings. Conceivably, the landing requirements could vary from an area that needs no special preparation, such as having the chipper operate on the road from logs decked at roadside, to a completely cleared forest area large enough for the chipper, and log deck, plus van turnaround. In these tests, landings averaged about one-half acre and were roughly square. They were slightly larger than those normally required for loading saw logs and pulpwood. Generally there are adequate openings for landings in the ponderosa pine type, with only minimum additional clearing required. In the spruce-fir type it may be necessary to completely clear a heavily timbered site. Landings must have sufficient level space for the Utilizer, which does not operate properly unless the two sections are well aligned. Ground conditions at the land-

ing must be sufficiently solid to withstand the weight of the Utilizer and loaded chip vans.

• Theoretically, it should be feasible for skidders to deck logs at a debarker-chipper landing within reach of the machine's self loader. However, only very small decks can be accumulated in this way, and such operation is essentially the same as hot logging. In practice, a front-end loader was needed at the landing to help sort and stack logs for easier loading into the debarker-chipper. The additional cost of the front-end loader, which can also be used for other purposes such as spreading bark, must be weighed against lower efficiency in operating the Utilizer.

• Moving bark away from the debarker-chipper was also a problem. The machine's self-contained equipment includes a transverse conveyor belt that can discharge bark to either side of the machine. To prevent clogging of the belt and its drive mechanism, the discharged bark must be cleared away frequently. In the test, the debarker-chipper "ground man" did this by hand in conjunction with the front-end loader, which bladed and spread or piled the bark. This method was time-consuming and not entirely satisfactory. In an ongoing operation, a secondary conveyor to move the bark farther away from the machine might be a better solution, even though it would make decking and loading more difficult on the discharge side and present an additional moving problem.

• The Utilizer may be moved from landing to landing as two separate units, as in over-the-road transport, or with the units hooked together in the operating mode. The latter method theoretically takes much less time since unhooking and rehooking operations are eliminated. Under the conditions of this test, however, it was often not feasible to move the Utilizer as one unit due to difficult terrain, poor road conditions, or lack of maneuvering space. A better arrangement for pulling the units from landing to landing should be developed. In the test a truck tractor was used, often assisted by the front-end loader or a skidder. In regular operation the manufacturer suggests the use of a dolly, equipped with a fifth wheel and tongue, that could be easily positioned under the front coupling of the Utilizer and attached to a crawler tractor or skidder.

5. Chips produced were of high quality.

Three general classes of pulp chips were produced in this test — debarked chips entirely from ponderosa pine, chips with bark from ponderosa pine, and debarked chips from combined live and dead timber of an uncontrolled mixture of Engelmann spruce and subalpine fir. All were found to be suitable for pulp production by the kraft process used at the Snowflake mill. Both classes of debarked chips compared very favorably with chips from other sources. Chips with bark, while less desirable, were satisfactorily processed without major changes in the pulping process by blending them with debarked chips. Chips from mixed dead and live Engelmann spruce and subalpine fir apparently caused no problems despite the fact that dead chips had an average moisture content of 42 percent, compared to 95 percent for live chips, based on the ovendry weight of the wood. The sieve size of chips produced from live timber was slightly larger than for dead chips, but the difference is probably not of practical importance.

6. Bark disposal at the chipping sites was not a major problem.

It was anticipated that bark accumulations at the inwoods chipping sites would present a major disposal problem. This did not prove to be the case. Ordinarily the concentration of bark was limited by the relatively small volume of timber chipped at one landing. Even in Colorado, where more than 500 tons of chips were produced at a single landing, the bark accumulation was not considered a major management problem, due in part to the large number of dead logs chipped that had little bark.

7. Environmental benefits were realized and impacts were less than expected.

Environmental benefits were expected from the inwoods chipping system as a result of additional slash removal. These benefits were generally realized. Some adverse impacts were also expected due to the need for larger landings, heavier road use, and bark disposal problems. These impacts were less than expected. Specific conclusions are:

The capability of utilizing material that would otherwise remain in the forest as debris under conventional logging practice was particularly beneficial in the Colorado test area. Large volumes of standing and down cull timber were utilized in addition to commercial thinnings.

Soil and site disturbance was generally comparable to conventional logging and within acceptable limits for forest management purposes. Bark disposal at chipper landings proved to be much less of a problem than expected. In Arizona, where bark was scattered and spread at the landing, the problem was nil. In Colorado, where the bark and unchippable chunks were piled for later disposal, the total accumulation was modest and disposal is not expected to create any more of a problem than conventional slash treatment.

Esthetic advantages of harvesting by this system, as compared with conventional multiproduct logging, were negligible in Arizona. In Colorado, considerable esthetic improvement resulted from removal of windthrown timber and other debris.

Other environmental impacts were not quantified, but a reconnaissance of the sites following harvest suggested that water runoff and stream sedimentation would not be significantly chang-

ed, wildlife and range habitat should be modestly enhanced, and timber regeneration prospects should be marginally improved. Despite significant differences in timber type and ground, terrain, and soil conditions, these environmental impacts were substantially similar on the two test areas.

THE PROBLEM

The Nation's requirements for wood and wood fiber are expected to rise dramatically in the remaining years of this century as a result of population growth, the energy situation, and other factors. These expanding requirements can be partially met by more intensive silviculture. However, due to the added investment required and environmental constraints, timber production will not likely increase as rapidly as requirements. The tendency will be for prices to rise and some needs to go unfulfilled. Within the past 5 years, two temporary periods of imbalance between requirements and available stocks have demonstrated the drastic consequences of a wood shortage. Meteoric price rises and unmet needs resulted in both instances from relatively small deficits between the wood and fiber sought and the amount available. One way to help offset such impending shortages is to use our existing timber resources more efficiently. This means, among other things, developing ways to utilize more of the trees and parts of trees that now go to waste.

Substantial progress has been made in fuller utilization of timber, but the wood and fiber yield of some forests could be further increased by as much as 50 to 100 percent if material not presently utilized could be economically harvested. While this degree of waste may seem intolerable, it cannot be easily corrected. The high cost of removing small trees and debris from the forest, compared to their relatively low value in industrial products, makes them generally uneconomic as sources of raw material. Having product prices rise sufficiently to cover these higher raw material costs is not a desirable alternative. Therefore, the most productive approach to complete utilization appears to be reducing the cost of harvesting, handling, and transporting these waste materials to a place of manufacture.

PURPOSE OF STUDY

The underlying purpose of this study was to find a more economical and more environmentally beneficial way to produce pulp chips from small trees and the residues left after conventional timber harvests. More specifically, the intent was to demonstrate an inwoods debarking-chipping system that is being used successfully elsewhere, and determine whether it is a feasible way to make pulp chips in the Four Corners region.

BACKGROUND

Wood to be chemically pulped for paper is chipped at some stage before it is reduced to fiber. These chips are fairly precisely engineered, generally 1/2 to 1-1/4 inches along the grain, about 1 inch across the grain, and about 3/16-inch thick. Conventionally these chips are made at the pulp mill from small logs (pulpwood), at sawmills from slabs and edgings, or from veneer waste at plywood plants. In recent years, however, interest has increased in producing pulp chips in the forest or at points intermediate between the forest and mill. Several operators in the South, East, and Northwest have adopted this practice and apparently find it advantageous. The incentives are to be able to economically utilize a higher proportion of the timber and residue available in a forest, and to reduce the cost of handling and transporting the wood from forest to mill.

The technology and economics of the pulp and paper industry generally permit only a small fraction of bark to be included in the pulp, since bark has a negative effect on both the properties of paper and the economics of processing. Thus pulp chips are usually made only from trees or residues that have the bark removed, and systems for producing pulp chips in the forest, as well as at the mill, necessarily include a debarking mechanism. The system tested in this study had both debarking and chipping capabilities and the pulp chips produced were of a quality comparable to those produced at mills. The cost is substantially higher than if the chips were made from wood with bark still attached, however. This latter approach, "whole tree chipping," has now become technically and economically feasible for some pulping processes, and is an alternative discussed later in this report.

Another important aspect of inwoods pulp chip production is the availability and location of markets for the chips. The market situation in the Four Corners region is unique in that only one regional firm produces pulp from raw wood — the pulp and paper division of Southwest Forest Industries, Inc., with production facilities at Snowflake, Arizona. While this limits competition for pulp chips, it simplifies analysis of potential supply and demand and makes the opportunities much clearer.

Southwest Forest Industries plans to substantially expand pulp and paper production at its Snowflake facility over a period of several years. It is obvious that more raw materials will be required. This company has therefore been very interested in inwoods chipping, both as a possible supplemental source of pulp chips, and because of potential forest management and environmental benefits.

Expansion plans for the Snowflake complex indicate that capacity will be increased from the current 500 to 1200 tons per day in the next few years. When the planned facilities are all on stream, daily capacity will be 450 tons of newsprint and 750 tons of kraft linerboard. Raw material for the expanded newsprint production will include 45 tons per day of mechanical pulp made from sawdust and 83 tons of semi-bleached kraft, supplemented by groundwood at an unchanged level of 180 tons per day. The remainder of the stock supply will come from recycling newsprint in the amount of 160 tons per day. The bulk of the raw material for the expanded linerboard production will come from increased recycling of waste container clippings and waste corrugated due to their cost advantage over additional chip sources. Chips produced in the forest could be an important supplement to these other raw materials in reaching the expanded production objectives.

Forest managers recognize that the availability of timber for harvest in the future will likely depend on the productivity of the forest and on the condition in which the forest is left after harvest. A major challenge in achieving standards satisfactory to the public and resource professionals is better management of overstocked stands and forest debris, including that resulting from timber harvesting. Forest managers therefore look upon inwoods pulp chip production as a potential tool in achieving such forest management objectives as proper thinning of stands and reduction of undesirable forest residues.

Another incentive for producing pulp chips in remote forest areas is the additional economic activity it would generate. Although this study did not include a detailed economic analysis, a summary estimate indicates that as many as 350 new jobs could result from the proposed Southwest Forest Industries expansion at Snowflake, with an additional annual payroll approaching $3 million. Pulp mill employment would rise by about 135, and an additional 215 workers would be required to provide raw material. Even if it were realistic to assume that only half of the increase would result directly from inwoods chipping, the gain would be significant and the economic benefits desirable. Based on multipliers reported elsewhere for the pulp and paper industry, total economic activity in the Four Corners region could be expanded by approximately $24 million per year.

A feature of inwoods chipping that makes it uniquely attractive for the Four Corners region is that this significant stage of production takes place and substantial value is added in remote areas where many of the region's economic problems lie. It would provide jobs and income for rural communities where these are often erratic or insufficient. Since pulp chips are already being hauled from sawmills scattered through much of the Four Corners region to the Snowflake mill, transportation from other remote communities may not present an insurmountable physical or economic problem. Also, there is the possibility that a railroad will be extended north from Gallup, New Mexico providing a less expensive alternative for moving chips to the pulpmill.

SPECIFIC OBJECTIVES

The specific objectives of this demonstration test were to:

1. Demonstrate to prospective entrepreneurs and others the operation of a portable debarking-chipping system under Four Corners conditions.
2. Explore the physical limitations of the equipment under Four Corners conditions.
3. Determine economic factors related to chip production with a field chipping system.
4. Define the optimum mode of operation for field chipping equipment.
5. Determine the quality of chips produced.
6. Evaluate the magnitude of the bark disposal problem at woods chipping sites.
7. Evaluate the environmental impacts and benefits of using field chipping equipment.

DESCRIPTION OF INWOODS CHIPPING SYSTEM

The production system analyzed in this demonstration test included combinations of men and machines conventionally used in the study areas for harvesting, coupled with a portable debarking and chipping machine located at landings in the woods. The system also included chip vans of the type normally used for over-the-highway transport of pulp chips.

Trees were felled, limbed, and bucked with chain saws by contract cutters, then bunched and skidded with rubber-tired or tracked skidders. Logs were stacked at the landing partially by the skidders and partially by a front-end loader. The self-loading debarker-chipper blew the chips produced directly into chip vans, which hauled them either to the pulp mill or a rail transfer point. The debarker-chipper worked from a cold deck rather than from logs skidded directly to it.

The central element in the system was the debarking-chipping machine. The unit selected to perform this function was the Logger Model Utilizer, manufactured by the Nicholson Manufacturing Company, Seattle, Washington. This unit, subsequently referred to as the Utilizer, inwoods chipper, or debarker-chipper, was selected because its characteristics seemed best suited to the local requirements. (See Appendix for specifications.)

One essential characteristic was the ability to produce bark-free chips, which at the time of machine selection was considered mandatory for pulp production at Snowflake. The Utilizer meets

this requirement with a high-performance ring debarker. A high production rate was also considered necessary for economic operation, and the Utilizer specifications indicated this capability with resulting low cost per unit of chips. The maximum diameter log that can be debarked in this model Utilizer is 18 inches, which was sufficient to handle most, but not all, of the material available for chipping. Minimum diameter that can be debarked is about 3 inches. There is no maximum limit on length, but logs must be at least 6 feet long to feed through the debarking unit without jamming. Figure 2 illustrates some of the size variation experienced in the test.

Fig. 2. — Variation in piece size typical of spruce-fir timber harvested in the test. Chippable material included many smaller pieces like those seen here.

Feed-rate for the machine when producing chips of the desired length of ⅝ inch is listed at 85 feet per minute. The Utilizer requires an operator who loads timber into the infeed conveyor and controls the debarking and chipping units. A ground man or assistant to the operator is required to perform general maintenance and to prevent and help dislodge jam-ups.

A front-end loader worked at the landing in conjunction with the Utilizer. The front-end loader removed bark from the end of the bark conveyor when necessary, and also repositioned logs from the log deck to put them within easy reach of the Utilizer's loader. Bark was spread on the landing in Arizona, but in Colorado, the bark was left piled for subsequent disposal.

Chips were blown directly into vans from the Utilizer. The position of the chip spout on the Utilizer required that the vans be filled from the rear. Vans were capable of holding from 8 to 12 bone dry unit equivalents (9.6 to 14.4 tons), depending on the size and moisture content of the chips. Chips were hauled directly from the Utilizer to the pulp mill from the Arizona test area. Chips from the Colorado test area were hauled by van to Gallup, New Mexico and reloaded on rail cars for the remainder of the trip to Snowflake.

Since in Arizona saw logs were also being harvested in conjunction with the chipping demonstration, timber to be chipped included both pulpwood trees and tops of saw log trees. Tops were cut from saw logs at the stump, but saw logs and timber to be chipped were skidded and decked together.

Five skidders were used on the Arizona test area: three large rubber-tired skidders with grapples, one rubber-tired tractor with choker cables, and one tracked skidder with choker cables. Saw logs were loaded and trucked to the sawmill before the remaining material was chipped. Although not anticipated, considerable reskidding was required after saw logs were removed to concentrate small decks into larger ones. Reskidding was believed to be more efficient than moving the Utilizer frequently.

In the Colorado test, most initial skidding was done by two skidders, one rubber-tired and the other tracked, both with choker cables. About two-thirds of the total volume was reskidded by two large rubber-tired skidders with grapples.

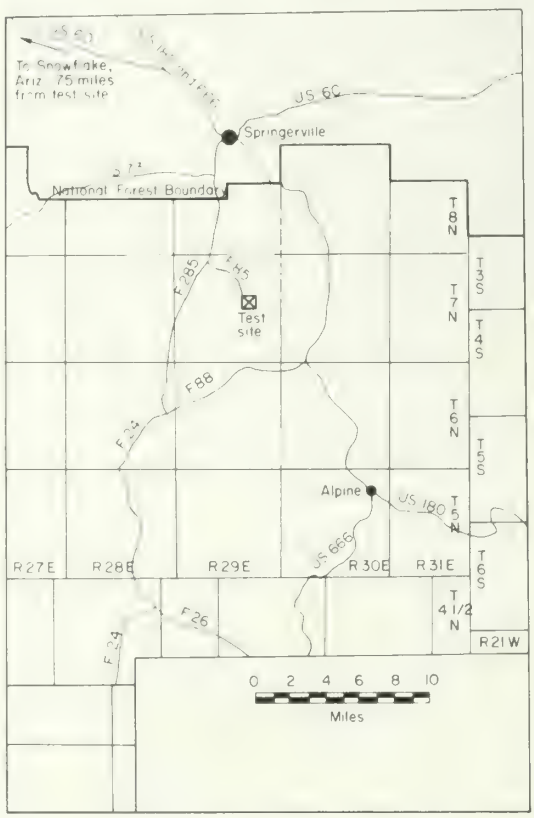

Fig. 3. — Location of the Canyon timber sale test site, Apache National Forest, Arizona.

CHARACTERISTICS OF TEST AREAS

The Arizona test area was on the Springerville Ranger District of the Apache National Forest (fig. 3). It was part of an ongoing multiproduct timber sale and included 276 acres. The timber type and topography are illustrated in figure 4. The uneven-aged timber stand was marked for partial cutting. Ponderosa pine was the predominant species with Douglas-fir, white fir, juniper, Gambel oak, and pinyon pine interspersed. There was very little down and dead timber on the test area, and none was skidded or chipped. Elevation on the test area varied from 8,100 feet to about 8,700 feet.

For the Colorado portion of the inwoods chipping test, logs were taken from a 36-acre tract on the Dolores Ranger District of the San Juan National Forest at an elevation of about 10,730 feet (fig. 5). Major tree species in the stand are Englemann spruce and subalpine fir. The tract had been logged for sawtimber more than a year prior to the inwoods chipping test.

The Colorado test area had a large volume of down and standing dead timber (fig. 6). Although the pulp mill had not previously utilized chips

Fig. 4. — Typical topography and ponderosa pine timber on the Apache National Forest test area.

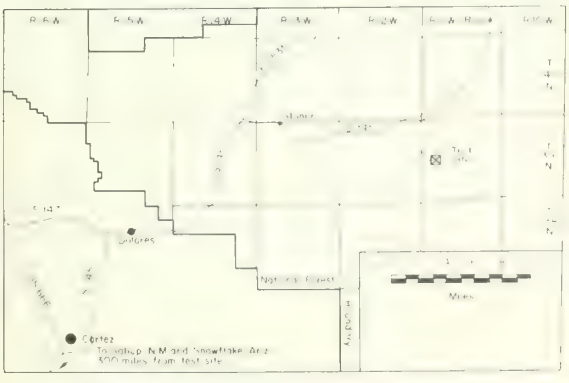

Fig. 5. — Location of the Roaring Fork timber sale test site, San Juan National Forest, Colorado.

Fig. 6. — The San Juan National Forest test area had large volumes of dead and down timber.

from dead timber, it was agreed that some would be harvested from this area. Therefore, all dead timber more than 50 percent sound was brought in with the spruce-fir thinnings.

DATA COLLECTION

Major data requirements in this study were stand characteristics; production costs, rates, and volumes; and resource impacts. To collect all necessary information and facilitate subsequent processing and analysis, special forms were developed for each type of data.

Plot Data

A full description of the forest stands on each test site was recorded to establish an environmental baseline. Future stand changes may be measured against these base data. Also, stand data on cut trees and residue pieces were used to help determine the volumes harvested in various categories, as discussed in later sections on chip yields and residue characteristics. Data were taken before harvest and again after harvest to determine the changes resulting from harvesting.

One-fifth acre plots were first laid out on maps of the sale areas. Locations were fixed by using a systematic grid system overlaid on the sale area map. On the ground a plot was located by pacing from reference points. It was then marked by a wooden stake at plot center, and by reference to two distinctive "witness trees." Site characteristics recorded were aspect, slope (percent), surface type, and brush density. Trees were classified by species, diameter, timber cutting mark (if any), crown class position, live or dead, and probable cause of damage if evidence was visible. Downed timber was also measured for inclusion in the residue category. To be included a piece had to be more than 4 feet long and greater than 3 inches in diameter at the small end. From these data, residue pieces which fit any specified inwoods chipping standard can later be "sorted out" and scaled for volume. As an example, since the Nicholson Utilizer could take only pieces greater than 6 feet in length and less than 18 inches in diameter, it was useful to be able to estimate the volume of residues within these limits. The computer program for plot analysis can be set up to screen the residue pieces for any desired range of dimensions if they are above the sampling minimum.

Shrubs and seedlings were counted on a second plot of 1/50 acre, concentric on the center of the 1/5-acre plot. Categories included the major tree species found in the stand, plus a breakdown of deciduous and evergreen shrubs.

Ground disturbance is one of the most visible environmental effects of logging. Selected plots were measured to determine the extent and severity of this damage. Proportions of the plot in a series of soil disturbance categories were determined by observing the soil surface at each of 50 steps along two radial transects from the plot center.

Harvesting Production Data

Data of several types were obtained for measuring production performance in the test, and for predicting performance under other circumstances. Generally, these data were collected for each of the basic harvesting functions in the form of time and motion measurements.

For felling and related functions, a stopwatch was used to measure the time required to fell, limb, and buck the tree, and for traveling from tree to tree. Factors that influenced these times include stump diameter, top diameter, species, distance between trees, ground surface, and ground condition. These data can be used to formulate predictive equations by regression analysis, and to establish statistical probability distributions for simulation modeling.

A similar approach was applied to data gathering for the skidding function. Time required for each part of the skidding cycle was recorded and correlated with factors most likely to influence performance, including skidding distance, amount of brush cover, ground slope, and ground surface condition. "Travel outbound" from the deck to felled trees is affected by these factors, as are the "bunch," "choke/grapple," and "travel inbound" subcycles. Other factors affecting the "bunch" and "travel inbound" subcycles are the number and volume of logs picked up and carried by the skidder. Information about the logs carried in each skid turn was recorded and used to compute volume.

Data On Inwoods Debarking — Chipping

The goal of gathering data on the inwoods debarking-chipping operation was to measure the Utilizer's productivity, and determine the patterns and causes of any delays or stoppages. Diameter of each log was pre-measured or visually estimated at the time of loading on the chipper. Log length was measured by a scale marked on the Utilizer infeed. Log type was determined according to the following breakdown:

Log type	Characteristics
1. Pulp log	A tree or butt log from a tree marked as a pulp tree, or a saw log or butt log from a saw log tree which was chipped because of poor quality.
2. Sawtimber top	An upper log taken from a sawtimber tree, or an upper log from a pulp tree.

3. Cull and salvage log	A log from timber that was down dead, or standing dead at the time timber was being felled.
4. Decked sawtimber cull	A log skidded and decked with sawtimber, but left behind as cull when the remainder of the saw logs were loaded. These logs usually had been decked more than a year.
5. Broken log top	Any green log which was broken on the large end. These pieces may have been broken during skidding, decking, or loading onto the chipper infeed, and couldn't be identified as coming from a certain log.

If a delay occurred during the normal work day, which usually extended from 0730 to 1630, it was recorded in "military" time, along with a code for the cause.

These general procedures were followed in both the Arizona and Colorado test areas. However, the high proportion of dead wood harvested in Colorado indicated a need to evaluate the characteristics of the chips produced more closely. Potentially, pulping characteristics and moisture content of the chips could vary significantly from log to log, depending on whether it came from a live or dead tree and, if dead, for how long. A better estimate of moisture content than could be obtained from the customary single sample per van load was particularly needed to establish the bone dry weight of chips produced. To meet this special requirement, chips produced from randomly selected live and dead spruce and fir logs were sampled as they were blown into the van. Larger chip samples were also collected periodically for shipment to the Forest Products Laboratory, Madison, Wisconsin, where they will be evaluated for pulping quality and potential use in particleboard.

RESULTS

Yield of Chips and Chip Quality — Arizona

Fifty-four van loads of chips from the Arizona test site were delivered to Southwest Forest Industries pulp mill at Snowflake. Chipping, exclusive of setup time, inclement weather days, weekends, and holidays took 31 days from June 25 to August 15, 1973. The gross weight of delivered chips was 1,288.9 tons. When converted to a bone dry basis, the net fiber weight was 49.2 percent of the gross chip weight, or 634.3 tons.

For all practical purposes, dead cull material contributed nothing to either volume or piece count in the Arizona test. Assuming these ponderosa pine timber stands are typical, there is little reason to expect much yield from dead or down trees from similar stands. Yield of green pulpwood on this multiproduct site averaged 161.4 cubic feet or 1.7 cords[2] per acre, less than many commercial pulpwood stands could produce. Table 1 summarizes the type and quantities of timber chipped on the Arizona test area.

Personnel at the Snowflake pulp mill were satisfied with the pulping qualities of chips supplied from the Arizona test site, including 10 van loads of chips produced from wood with bark still attached, sent to the mill for test purposes. Qualitative results of these tests indicated no appreciable difference in pulp quality, since only small proportions of undebarked chips were blended with debarked ships.

Yield of Chips and Chip Quality — Colorado

Forty-eight van loads of chips were produced in 18 days of chipping on the Colorado test area. Gross weight of these chips was 801.5 tons. Bone dry weight was 63.1 percent of the gross weight, or 505.4 tons.

Although the number of pieces of dead material (2,683) was slightly less than the number of green pieces (2,717), dead material contributed significantly more volume. Green pulpwood averaged 515.9 cubic feet of solid wood or 5.3 cords[2] per acre. Dead and cull material contributed 830.9 cubic feet or 8.5 cords per acre, 61.7 percent of the total volume chipped from the test area. Much of the dead timber was blow down, some of which occurred after a saw log harvest over a year before the chipping test. This yield pattern may have important implications for spruce-fir forest areas where a general woods cleanup of dead and down timber could be combined with a conventional pulpwood harvest. Currently, however, no pulpwood is harvested in Colorado. Table 1 details chip yield statistics for the Colorado test area.

A preliminary evaluation indicated that chips from both live and dead wood can be pulped satisfactorily by the sulfate pulping process used at the Snowflake mill.

Further analysis of these chips produced in Colorado indicated that moisture content differed significantly between chips from live and dead trees, as would be expected. The average moisture content of chips from live trees was 95 percent, contrasted with only 42 percent for chips from dead trees. There was also a significant difference in moisture content between chips produced from live Engelmann spruce and from live subalpine

[2]*The conversion of cubic feet to cords assumes 97.8 cubic feet of solid wood per cord.*

Table 1. — Summary of Arizona and Colorado harvest statistics by log type

Log type	Pieces chipped		Volume chipped		Ave. volume per piece
	No.	% of total	Cu. ft. of solid wood	% of total	Cu. ft. of solid wood
Arizona					
Green					
Pulp tree	4,681	72.3	29,426	66.5	8.0
Sawtimber top	1,910	30.2	13,260	29.8	6.9
Broken log tops	676	10.7	1,557	3.5	2.3
Subtotal	6,270		44,243		7.0
Dead					
Cull and salvage	49	.8	286	.6	5.8
Cull decked sawtimber	1	.0	17	.0	17.0
Subtotal	50		303		6.1
Total	6,320	100.0	44,546	100.0	7.0
Colorado					
Green					
Pulp tree	2,373	43.9	17,675	46.5	7.4
Sawtimber top	5	.1	7	.0	1.4
Broken log tops	339	6.3	889	1.8	2.6
Subtotal	2,717	50.3	18,571	38.3	6.8
Dead					
Cull and salvage	2,678	49.6	29,902	61.7	11.2
Cull decked sawtimber	5	.1	12	.0	2.5
Subtotal	2,683	49.7	29,914	61.7	11.2
Total	5,400	100.0	48,485	100.0	9.0

For a definition of the log type, refer to the section on Data Collection.

fir — 82 percent versus 107 percent, respectively. Moisture content of chips from dead material did not vary significantly with either species or log diameter, however.

The average chip size, as measured by a standard sieve method, was 0.51 inch for spruce and 0.50 inch for fir, not significantly different. Chips from live timber averaged 0.53 inch while those from dead timber averaged 0.49 inch. Though statistically significant, this difference is probably of little practical importance.

Costs

The total costs of getting timber from the stump into pulp chips and then delivered to the pulp mill are shown in table 2. Costs for the individual functions involved in inwoods chipping are also shown for the two test areas and for a conventional multiproduct system in Arizona.

The assumed machine and labor rates used in computing costs are shown in appendix table 4. The hourly and daily cost computations for the Utilizer are given in appendix table 5.

Except where noted, the costs actually experienced are given. A major exception is the computed chipping cost used. In computing this cost we eliminated downtime due to problems believed to be peculiar to this study and not likely to be encountered in an ongoing operation.

Falling, Limbing, and Bucking

Costs of falling, limbing and bucking timber from a selection cut in a ponderosa pine stand should be slightly less with inwoods chipping than if roundwood pulpwood were produced. The reason for this is that roundwood pulpwood must be measured and cut to lengths in multiples of 5 feet. With inwoods chipping, slightly longer lengths should be obtained than for pulpwood roundwood, although slightly more time may be required for limbing. In the field test, falling, limbing, and bucking required 17.2 minutes per hundred cubic feet for inwoods chipping versus 20.7 minutes per hundred cubic feet when roundwood was produced. Limbing and bucking took about 0.3 minute longer per tree when it was necessary to measure pulpwood lengths. Top diameters were about 0.4 inch larger (inside bark) where pulpwood was cut to lengths in multiples of 5 feet. However, the cost of falling was contracted at the same rate for conventional multiproduct harvest and inwoods chipping as reported in table 2.

Table 2. — Total unit cost of chips delivered to the Snowflake pulp mill from the test areas in Arizona and Colorado, in comparison with a conventional system for producing chips (cost of stumpage excluded)

Function	Inwoods chipping[1]		Conventional multiproduct system in Arizona (ponderosa pine)
	Ponderosa pine (Arizona)	Spruce-fir (Colorado)	
	Dollars per bone dry unit[2]		
Falling, limbing and bucking	4.60	4.26	4.60
Skidding and decking	9.08	7.75	9.08
Reskidding	2.92	2.29	—
Loading pulpwood	—	—	2.80
Chipping	19.46	18.51	—
Total inwoods cost	36.06	32.81	16.48
Truck haul pulpwood	—	—	4.36
Slashing to 5' length	—	—	7.12
Rail haul pulpwood	—	—	3.53
Chipping	—	—	3.20
Truck haul chips	13.64	24.86	—
Scale and record	—	.40	—
Rail haul chips	—	7.89	—
Unloading, scaling, etc.	.40	.40	.75
Total out-of-woods cost	14.04	33.55	19.16
Total cost	50.10	66.36	35.64

Costs for inwoods chipping are based on production of 398.6 bone dry units in Arizona and 421.1 bone dry units in Colorado.

A bone dry unit is 2,000 lbs. of chips at zero moisture content. This unit is roughly equivalent to a cord.

Cost adjusted to eliminate downtime that could probably be eliminated in an ongoing operation.

In the spruce-fir type in Colorado, the volume of down timber inhibited movement of the timber faller and made limbing and bucking very difficult. Diameter of the timber being felled in this area was slightly smaller than in Arizona. The average rate was 36.5 minutes per 100 cubic feet.

Skidding

For green timber, utilization is slightly greater with inwoods chipping than when logging roundwood due to slightly smaller top diameters. Skidding rates and costs should be comparable between the two systems, with skidding for inwoods chipping having a slight advantage because of slightly increased volume per

piece. In practice, however, considerable reskidding or forwarding was done to increase the volume of wood available at individual landings. This obviously increased total skidding costs, but reduced the cost of moving the Utilizer and preparing additional landings.

Initial skidding on the ponderosa pine area in Arizona averaged 22.7 minutes per 100 cubic feet for the five skidders. This production rate is quite low compared with skidding observed in large sawtimber stands (typically less than 6 minutes to skid 100 cubic feet), but it is better than that observed in skidding selectively cut ponderosa pine pulpwood on similar terrain (30.8 minutes per 100 cubic feet). The terrain was undoubtedly a factor in reducing skidder production in this test, since abrupt changes in topography interfered with skidder travel. The skidding cost for Arizona reported in table 2 is that reflected by company records.

On the spruce-fir test area in Colorado, higher volume per acre and more favorable terrain but longer distances resulted in 27.2 minutes of initial skidding time per 100 cubic feet. The average initial skid distance was less than 200 yards. About two-thirds of the volume was reskidded, however, with reskid distance averaging about ¼ mile.

Debarking-Chipping

No major differences in production rates or costs were expected for falling or skidding functions in the inwoods chipping system as compared with conventional multiproduct harvesting. The main interest in this study was therefore the actual debarking-chipping operation.

Data furnished by the chipping machine manufacturer prior to the demonstration test, adjusted to the conditions expected in the test, indicated that the debarking and chipping cost should not exceed $6.60 per unit (including cost of a front-end loader accompanying the chipper). We therefore anticipated substantial net economies, since inwoods chipping would eliminate the need for a pulpwood yard, where the cost of cutting logs into pulpwood lengths and reloading them onto rail cars was running about $7.12 per cord, as well as the $3.20 per unit cost of chipping at the mill. These economies were not realized in the test, primarily because the debarker-chipper had much more downtime due to mechanical problems than expected, and production rates when the machine was running were less than expected. It also took considerably longer to move the machine between landings than had been predicted by the manufacturer. Much of the excessive downtime can probably be attributed to the extensive modification of the machine's power plants that was necessary to permit it to operate at the test elevations. The machine's mobility could also be improved with some fairly minor changes in the towing arrangement, which would be practicable in an ongoing operation. Where possible, such improvements have been taken into account in projecting long-term costs of an inwoods debarking-chipping system.

Operation of the debarker-chipper was monitored continuously throughout the study. Starting and ending times for chipping each van load were noted. Any delays of one minute duration or longer were noted along with the cause. An analysis of these times showed that the machine was operating only 54.1 percent of the total available time (time when the Utilizer either was producing or could have been had it not been broken down or jammed). It had been anticipated that the machine would be producing chips during more than 80 percent of the available time.

Actual production rates were 7.9 units per net operating hour in Arizona and 7.6 units per hour in Colorado, compared with 10 units that had been projected. The reduced rate was due to (1) difficulty in loading timber into the machine fast enough to utilize its full debarking-chipping capacity, and (2) slowdowns of the chipper resulting from power loss at high altitudes. The high altitude was more of a factor in Colorado than Arizona because of the large proportion of dry dead timber, which requires greater power for chipping.

The loader unit on the Utilizer was designed for six load cycles per minute. In preliminary analyses a maximum of four cycles per minute was assumed to allow for delays in grappling and positioning logs. In actual operation, however, the loader was seldom able to average more than two pieces per minute in producing an entire van load of chips.

Moving the debarker-chipper from landing to landing also presented some unexpected problems. According to specifications, if the debarker-chipper units were left coupled, it should take 5 minutes to prepare for moving; then the machine could be moved at the rate of 100 yards per minute, and 5 minutes would be required to set the machine at the new landing. If the two units were to be uncoupled, it would take 20 minutes of preparation; then the units could be moved at 30 miles per hour over good roads, and 20 minutes would be required to recouple the units and set the machine at the next landing. Actual moving times were much greater than predicted. Minimum moving time was 55 minutes if the two units were left coupled and 95 minutes if the two units were uncoupled and moved separately.

Moves were usually short (between 100 and 400 yards). In the ponderosa pine test area there were 11 landings and 10 moves of the Utilizer. It was therefore desirable to move the machine in one piece if possible. However, terrain features required that the Utilizer sometimes be moved in two units, even where moves were short. The average moving time used for determining chipping costs was 65 minutes, based on the assumption that on ¼ of the moves the Utilizer would have to be moved as two separate units.

Hauling

Ton mile costs for a chip van should be about the same as for a log trailer, but about 10 percent of the weight of roundwood pulpwood is bark, so, hauling debarked chips should be somewhat cheaper. Actual hauling costs depend in part on efficiency of the debarker-chipper. Volumes hauled per day will decrease and the cost per unit increase if vans are not fully utilized.

The chip hauling costs in Arizona included a round trip cost of $92 from the woods to the Snowflake mill (75 miles) and a rental cost of $25 per day for each of five vans. This gives a total hauling cost of $13.64 per unit for a production rate of 29.4 units per day.

In Colorado, chip hauling was contracted for $140 per round trip from Dolores, Colorado to Gallup, New Mexico (146 miles), an average of $15.96 per bone dry unit. There was also a cost of $150 per day for two truck tractors used to shuttle loads from the woods to Dolores. A cost of $25 per day was added for rental on each van. Thus, the total truck hauling cost for a production rate of 30.9 units per day in Colorado was $24.86 per unit to Gallup, a total distance of 184 miles. The rail hauling cost from Gallup to Snowflake, a distance of 116 miles, was $7.89 per unit of chips, plus $0.40 per unit for weighing and reloading on rail cars. The total average hauling cost for chips produced in Colorado was therefore $33.55 per unit.

This high transportation cost alone makes Colorado questionable as a source of chips, even with significant reductions in cost of inwoods chipping. However, increasing demand for pulp and a resultant price increase, coupled with a limited wood supply close to the pulp mill, could make Colorado pulpwood harvesting feasible in the future. Also, there are prospects for a new rail line to be constructed about 100 miles north from Gallup for other purposes. Assuming this rail line would be available to Colorado shippers, substantial reductions in freight costs for Colorado-produced pulp chips should be possible.

Projected Inwoods Debarking-Chipping Cost

Chip production in these tests averaged only 15 bone dry units per day over the 63-working-day period the debarker-chipper was available for operation. At this rate the cost of chipping would be about $38 per unit. Obviously, this cost is too high to be economic for pulp production under present conditions. However, the 63-day period included much time lost due to kinds of delays typical of pilot operations. Such factors as organizing and training the crew to operate an unfamiliar system, getting the debarker-chipper to run properly at high altitudes, logistic problems stemming from lack of experience, and many other delays greatly reduced the time in production and therefore raised unit costs.[4] While it may be argued that this was the actual experience and represents the best estimate of productivity, we consider it unrealistic to use this rate as a basis for projecting costs for an ongoing operation. To get a more realistic view of long-term performance, we have assumed that many of these inefficiencies could be eliminated over time, and that the improved levels achieved would provide a better basis for cost estimates. Since the degree of improvement expected is judgmental, we have projected costs under several sets of assumptions, as depicted in curves I through V, Figure 7.

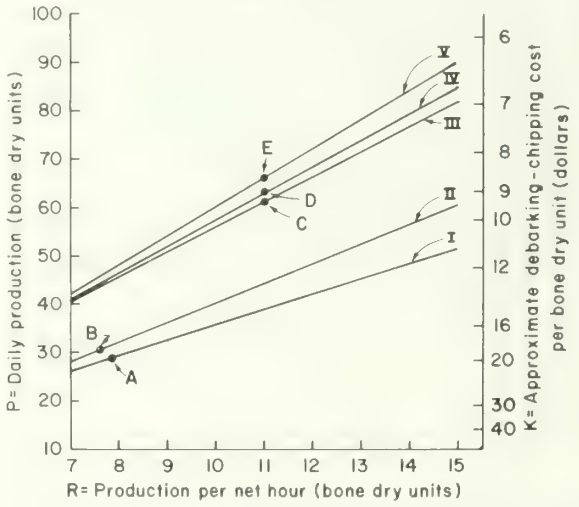

Fig. 7. — Daily chip production and approximate chipping cost by net production rate according to log deck size, proportion of available time in production, and moving time between log landings.

The equations for the two ordinates or vertical scales of the curves in figure 7 are given by

$$P = \frac{H}{\frac{1}{RT} + \frac{M}{U}} \quad \text{and} \quad K = \frac{572.16}{P}$$

where:

P = daily production in units of chips.
H = hours per day available for moving Utilizer or chipping.

[4] *Time available for operation in the test totaled about 500 hours. Of this total time only about 128 hours were actually spent in producing chips. The remainder of the available working hours included approximately 107 hours when the debarker-chipper was inoperable; 15 hours for routine maintenance; 28 hours for moving the debarker-chipper (which could possibly be reduced to 10 hours with improvements in design and crew experience); 60 hours spent waiting for vans at the chipper; 15 hours to change vans; 20 hours required to move from one test area to the other; 40 hours attributable to logistic and crew delays; 45 hours lost due to weather conditions; and 40 hours lost for other miscellaneous reasons.*

R = units of chips produced per net production hour.
T = percent of time available for chipping that the machine is actually in production as a ratio.
M = moving time (in hours) between decks.
U = average number of units per deck.
K = cost per bone dry unit.
572.16 = daily cost of operating Utilizer system.

Note that the abscissa scale is in terms of R, and five combinations of the remaining variates as shown below account for the different curves.

Curve	T	U	M
I	54	48	1.08
II	54	—	None
III	80	48	.40
IV	80	80	.40
V	80	—	None

In addition it was assumed that 7.5 hours per day were available for chipping or moving for each curve.

Curve I represents conditions similar to those that would have been encountered on the Arizona test area if startup problems and weather delays were eliminated. (The cost of weather delays is discussed further in a later paragraph of this section.) Point A on this curve represents the 7.9 bone dry units per net production hour experienced in actual operation. A daily production rate of 29.4 bone dry units results from this hourly rate when operating hours are reduced to reflect experienced downtime on the Utilizer, including moving time at a level that should be attainable. Production cost at this rate is $19.46 per unit.

Curve II generally represents conditions that would have been encountered in the Colorado test area without startup and weather delays. Point B on this curve represents the 7.6 bone dry units per net production hour experienced in actual operation. A daily production rate of 30.9 units results from this hourly rate when operating hours are reduced to reflect experienced downtime on the Utilizer. Move time was not deducted since all production was at a single landing. Production cost at this rate is $18.51 per bone dry unit.

Since the proportion of time the debarker-chipper was actually in production seemed to be less than could be expected in an ongoing operation, curves III, IV, and V were developed to reflect more probable and economically necessary levels. The Utilizer's production rate while actually operating also appeared to be lower than should be achieved with further experience. It is therefore assumed that a production rate of 11 bone dry units per net operating hour should be possible for most types of timber. This assumption is represented by Point C on curve III, with a resultant daily production of 61.5 units at a cost of $9.30 per bone dry unit.

The unit cost difference between Points A and C is $10.16. Of this, $5.67 is attributable to changing the proportion of operating time from 54 to 80 percent, $3.41 to increasing production per net hour from 7.9 to 11.0 units at 80 percent operating efficiency, and $1.08 to decreasing moving time between landings from 1.08 to 0.4 hours. Changing the average deck size at Point C from 48 units to 80 units results in Point D on curve IV, where daily production is 63.2 units at a cost of $9.05 per unit.

If all assumptions about Point D were retained and it were further assumed the machine was at a semipermanent location (no moving time), daily production would be 66 units, reflected by Point E on curve IV. Cost per unit would be $8.67, or a reduction of $0.38 per unit from Point C.

The most critical assumption in decreasing debarking-chipping costs is the ability to increase the proportion of operating time from 54 to 80 percent of available time.

Inclement weather would likely cause some downtime because of road conditions in an ongoing operation as it did in the test. A downtime of 10 percent, with only fixed costs for the Utilizer and front-end loader being incurred, would result in an increase in unit cost of chipping of $1.24, $1.19, $0.60, $0.58, and $0.55 for points A through E, respectively. Downtime of 20 percent for weather would increase cost per unit $2.79, $2.66, $1.34, $1.30, and $1.24, respectively.

Fixed costs for the Utilizer system are based on an operating season of 1600 hours per year. While it would be difficult to operate "inwoods" for this period of time even in Arizona, it was felt that an owner of such a system would operate at least 9 months and probably year round, even if it meant locating at a mill yard or other intermediate location for several months. Problems and advantages of operating at an intermediate location are discussed in a separate section later in the report.

ENVIRONMENTAL FACTORS

A major objective of this demonstration test was to determine how the inwoods chipping system would affect various environmental factors. It was assumed that the basic harvesting functions would have the same impact as in the conventional systems, since they were essentially similar, but the greater removal of forest residues would be an environmental improvement. Such removal would improve esthetics, and provide better protection from fire, insects, and disease.

Bark accumulation was the one expected negative factor in inwoods chipping. In practice, the environmental effect of the waste bark proved to be negligible in Arizona and easily managed in Colorado.

While exacting techniques for measuring environmental impacts were either unavailable

or outside the scope of this study, we attempted to evaluate them as thoroughly as practicable.

The reduction in volume of residues was analyzed most definitively. Site sampling and reconnaisance also provided a useful index of soil disturbance. A new experimental technique is being used to evaluate the esthetic improvement obtained by this harvesting system (Daniel, et al. 1973). It will be some time before the results of this analysis are known.

While this attempt at evaluating the environmental effects of harvesting in an objective frame of reference is not as definitive as we would like, it provides some useful information and paves the way for further development needed in this field. The following summarizes the results of the environmental evaluations.

Residue Left After Debarking and Chipping

As would be expected, timber stand differences in Arizona and Colorado resulted in different amounts and distributions of residue remaining after harvest. The major differences are that Colorado spruce-fir stands typically are denser and have more down timber than Arizona ponderosa pine stands. Table 3 summarizes estimated residue volumes and pieces, by size category, left on the ground after the chipping.

Before logging, the Arizona test site had little chippable residue, as is typical of many southwestern ponderosa pine stands. Following harvest, very little residue remained from the volume generated by logging except branch material not classified as chippable (fig. 8). The volume of green residue left, within the Utilizer size limits, amounted to 14.1 cubic feet per acre. Dead chippable residue was only 2.1 cubic feet per acre. Thus, the total chippable residue after harvest was 16.2 cubic feet per acre. Even if the Utilizer could have effectively processed material less than 6 feet long, only an additional 0.1 cubic feet per acre could have been utilized.

Table 3. — Characteristics of residue remaining on the test area after inwoods debarking-chipping

Type of residue	Volume per acre		Pieces per acre		Volume per piece	
	Ariz.	Colo.	Ariz.	Colo.	Ariz.	Colo.
	Cu. ft.		Number		Cu. ft.	
			Green			
6 ft. long	0.1	4.2	0.4	11.4	0.3	0.4
6 ft., large end dia.						
18 in.	14.1	9[illegible]	7.9	68.2	1.8	1.4
6 ft., large end dia.						
18 in.	0	75.7	[illegible]	5	0	168.2
			Dry			
[illegible] large end dia.		13.1	0	11.8	0	1.1
6 ft., large end dia.		[illegible]	1.1	61.4	2.0	3.0
[illegible]		57.1	.4	1.8	38.2	31.4

In contrast to Arizona, residue on the ground before logging for inwoods chipping provided a significant part of the chip volume in the Colorado test (fig. 6). However, relatively more residue volume remained after chipping in

Fig. 8. — Unchippable ponderosa pine slash remaining after harvest on the Apache National Forest test area.

Colorado than in Arizona because of the large number of marginal pieces that technically qualified for the "chippable" category but were not harvested. Green "chippable" residue not chipped averaged 95.5 cubic feet per acre. However, it was contained in 68.2 pieces per acre, so each piece had an average volume of only 1.4 cubic feet. This figure compares closely with the 1.8 cubic feet per piece left on the ground in Arizona. More dead or dry residue remained on the ground in Colorado than in Arizona. But since the number of pieces was also much greater in Colorado, the average dead piece volume was about the same for both areas. Many residue pieces were barely within the "chippable" category, as defined by Utilizer size limits. These small, marginal pieces are easily overlooked by the skidder operators, and therefore may not be brought to the chipper. It is also apparent that substantial volumes were not chipped because the diameter of the pieces exceeded the 18-inch capacity of the debarker.

Soil Disturbance

A survey of the soil cover disturbed by logging on test sites indicated that the degree of disturbance (percentage of soil surface) was proportioned as follows:

	Ariz.	Colo.
1. NONE — no disturbance	38.6	46.4
2. NONE/SLASH — soil not disturbed; covered with residue from logging, or natural disaster.	29.4	22.0
3. LIGHT — observable wheel marks of skidders, etc.; no mineral soil exposed. Litter layer packed; brush layer broken down or bent over. Skidder generally traveled in an area only once.	15.1	16.1
4. MEDIUM — machine wheels or logs broke through litter layer. Mineral soil exposed and compacted. Shrubs broken down. Machines traveled on the same trail several times; wheels did not break into the root mat.	7.9	9.3
5. HEAVY — same conditions as in MEDIUM, with addition of heavily rutted trail and roots severed. Trail used several times as a main trail for long skidding distances. In dry weather, surface dust layer loose and thick. In wet weather, trail can deteriorate rapidly with only a few trips.	9.0	6.2

The proportional area of disturbance was essentially the same on the Arizona and Colorado sites. Both the total proportion of disturbed areas and the proportions of areas in the HEAVY, MEDIUM, and LIGHT disturbance classes were similar. From available evidence in other studies and our results in Arizona and Colorado, it appears that ground disturbance by tractor skidders is quite similar over a wide variety of terrain, logging systems, and timber types (Zasada and Tappeiner 1969, Campbell et al. 1973). In the Zasada and Campbell studies, as well as in this study, topography or logging methods appeared to limit the amount of surface that is heavily disturbed. Zasada's study was done on flat terrain, but repeated runs by skidders were channeled into certain areas. In Campbell's study, steep to rolling terrain naturally limited the placement of effective skid trails.

Average slope on the Arizona test site was 21 percent with a wide variety of terrain. Slope values ranged from 5 to 55 percent. Main skid trails and spur roads were located on the contour as much as possible. In Colorado the test area was located on a ridge top, where the slope was flat to gentle in the upper portions and steeper on the lower parts of the site. Slopes ranged from 2 to 33 percent, with the average being 16 percent. Heavily traveled skid trails could only be placed on the contour and on the ridge top.

Fire Danger

No quantitative attempt was made to determine whether inwoods chipping reduced fire danger compared to conventional pulpwood and multiproduct harvesting. Qualitatively, some minor improvement should be realized in the ponderosa pine type, since volume utilized in the chipping harvest was slightly greater than in conventional pulpwood harvesting due to cutting to a set top diameter rather than 5-foot multiples. Some additional cull material was removed also. Chipping in conjunction with a sawtimber harvest should yield greater benefits, giving about the same net effect as a multiproduct harvest plus the marginal additional benefit relative to pulpwood harvesting.

Other fire-related aspects of ponderosa pine harvesting are essentially the same for these systems. Volume and distribution of branches and needles should be the same, but lopping of tops, required as a fire precaution under most timber sale contracts, may be slightly less time-consuming for inwoods chipping since the diameter of the cut tops will average nearly a half-inch smaller.

In the spruce-fir type in Colorado, an abundance of standing and down dead timber was harvested for chipping. This dead material amounted to slightly over 60 percent of the total volume chipped from the Colorado test area. More than seven units per acre which would have remained as residue under conventional sawtimber harvest were removed. This substantially reduced the total fuel available, and should reduce the hazard of a major fire. It would not have much effect on the initial rate of spread, however, since the residues removed were too large. Improved accessibility would simplify suppression activities.

Esthetics

The greater the quantity of down limbs and timber and the greater the signs of disturbance, the less esthetically pleasing a forest stand seems to be. Considering the small amount of debris present either before or after harvest, it is doubtful that inwoods chipping in the Arizona ponderosa pine type will produce an effect esthetically distinguishable from conventional harvesting to a 4-inch top. When sales contracts call for harvesting trees to an 8-inch top, however, the esthetic benefits of chipping would likely be more obvious.

In the spruce-fir type in Colorado the esthetic impacts of harvesting were potentially much greater. Much of the large volume of dead and down material in these stands was chipped (fig. 9). On the other hand, the removal of large volumes per acre resulted in greater disturbance of the site.

In an attempt to evaluate these esthetic impacts, photographs were taken before and after harvest for the inwoods chipping test. These photos are being analyzed by an experimental process involving review by various audiences to determine comparative esthetic values before and after harvest. Since much of the evidence of harvesting disappears after a year or two, the test areas will be rephotographed 2 years after harvest. These photos will also be evaluated by the panel technique to determine the change in esthetic values.

Fig. 9. — Before and after harvest views of a scenic vista on the San Juan test area.

Other Environmental Factors

It is doubtful that harvesting on either of the two test areas had a measurable effect on other environmental factors.

The volume of timber removed from the ponderosa pine area was quite small, and probably would not noticeably affect water yield or insect and disease potential. Since the harvest did open up the stand, there will likely be some increased growth of forbs and grasses for a few years, and consequent improvement in range and wildlife habitat.

The large volume of dead and down timber removed in the spruce-fir stand may initially accelerate runoff due to the removal of physical barriers, which might slightly increase sedimentation. The removal of physical barriers should also make the area more accessible to big game, but perhaps less desirable for some small-game and non-game species.

More will be learned about the actual effects of harvesting on these environmental factors when the test areas are revisited in subsequent years.

FUTURE DEVELOPMENT OF HARVESTING SYSTEMS FOR PULP CHIPS

The experiences gained in this demonstration test provided considerable insight into how the system might be improved and modified to meet Four Corners conditions. Overall reduction in unit costs is obviously the major challenge.

Intermediate Locations

An alternative to debarking-chipping in the woods or at the pulp mill is to perform these operations at some intermediate point. The debarker-chipper could be set up at one or more semipermanent or permanent locations where it would operate several months at a time or year round. In theory, the same degree of timber utilization could be achieved at such intermediate locations as is possible with inwoods chipping. Instead of chipping at a woods landing, timber to be chipped would be trucked to the intermediate location for debarking and chipping. There chips would be blown into a van or rail car and hauled to the pulp mill.

Advantages foreseen for debarking and chipping at an intermediate point compared with an inwoods location include:

1. Greater proportion of time available for chipping, due to elimination of debarker-chipper moving time.
2. Less downtime due to weather.
3. Easier travel by chip vans, due to no inwoods travel.
4. Greater output per net hour of production, due to greater efficiency in loading.
5. Availability of line electric power for the debarker-chipper, which is more efficient, more trouble-free, and less costly than diesel power.

Possible disadvantages are:

1. Increased handling costs and breakage of small timber due to the extra loading and handling.
2. Increased log hauling costs and problems of getting short pieces loaded on log trucks in the woods.

3. Bark disposal problem at debarking-chipping site.
4. Large inventory space required for concentrating timber at debarking-chipping yard.

Curve V of figure 7, which estimates production if the Utilizer is not moved and downtime due to mechanical breakdown and log jams is reduced to 20 percent of available time, most closely approximates a debarker-chipper operating in a semipermanent setting. If the Utilizer could be redesigned to reduce the time required to move from landing to landing to 0.4 hour as shown by Curves III and IV of figure 7, the debarking-chipping cost advantage at an intermediate location would probably be negated by the additional costs of loading and hauling timber and bark disposal.

There is, of course, the additional consideration of being able to work a longer season and during inclement weather at an intermediate location when an inwoods operation would be shut down. The optimum situation would probably be to debark and chip in the woods in the spring, summer, and fall, and move the Utilizer to a concentration yard during the winter.

A variation on debarking-chipping at intermediate locations would be to chip at a timber concentration or log sorting yard. Logs from surrounding areas are hauled to these yards to provide a better opportunity to sort for alternative uses than deck sorting in the woods, and highly mechanized handling systems permit sorts to be made more efficiently. There is a growing interest in sorting yards in the southern Rocky Mountains; one is already under construction, and there are plans for at least two more to be built within 4 years.

Justification for such sorting yards will depend largely on increasing the value of sawtimber by better log sorting. Chipping at a sorting yard instead of in the woods would seem to be more economical, provided the presence of pulpwood did not create a bottleneck for the log sorting operation. Pulpwood could be brought in in any length, and could either be chipped or bucked into the lengths needed for groundwood. Odd lengths and crooked pulpwood as well as cull saw logs could be chipped at the sorting yard and hauled to the pulp mill in chip form.

Whole-Tree Chipping

One promising way to lower chip costs is to eliminate the debarking requirement. There has been much interest recently in whole-tree chipping — that is, chipping the tops, limbs, and foliage, as well as the bole wood. This requires that chipping be done in the woods, since it is impractical to load and haul whole trees to a mill. It also means that the bark is chipped along with the wood, since it is not feasible to remove bark from very small or crooked material.

Advantages of this system over debarking and chipping in the woods are:
1. It eliminates limbing and thus reduces cost.
2. Since there is no debarking, inwoods equipment and processing are simpler and less costly.
3. Slash disposal is eliminated.

Disadvantages include:
1. Skidding whole trees is probably more expensive and results in more damage to reproduction and the site.
2. The utility of the chips produced is restricted.
3. Special processing is required for whole-tree chips.
4. The waste disposal problem at the mill is increased due to the presence of bark and needles mixed with the wood fiber.
5. Nutrients from the needles and branches are not returned to the site.

There is no doubt that whole-tree chipping can deliver chips to the mill at a lower cost than inwoods debarking-chipping. The two disadvantages that are likely to limit its adoption are damage to the residual stand during skidding, and the need for special processing at the pulp mill. Conventional pulping processes can accommodate only small amounts of bark. While a process for separating bark from whole-tree chips has been developed, it is still in the experimental stage. However, some chips now produced from whole trees in other parts of the United States are being successfully used in paper and other products without complete bark separation.

Multiproduct harvesting, with chipping of whole pulp trees and whole tops of sawtimber, would require limbing the saw log portion of trees and making buck cuts between sawtimber and pulpwood, either at the stump or at a landing. On stands being partially cut, skidding of large whole trees would probably be unacceptable due to damage to the site and the residual stand. Skidding of whole trees should be acceptable on areas being clearcut, and saw logs could be limbed and bucked at the landing.

It seems unlikely that whole-tree or sawtimber-top chipping on multiproduct sales will ever be feasible on partially cut ponderosa pine stands due to skidding damage. In spruce-fir stands, however, because of the general shape of the trees, the site and residual stand are less likely to be damaged when trees are skidded whole.

If whole-tree chipping for pulp chips becomes practicable in this area, it will likely be because of cost reductions in harvesting and not because of the increased volume of pulp chips obtained per harvested tree. The branches and tops now being left in the woods that would be salvaged with whole-tree chipping are small in diameter, and a high proportion of their volume is bark. The yield of acceptable pulp from bark is very low compared to bark-free wood. A prerequisite for any whole-tree chipping, of course, is a process that can economically utilize chips with bark.

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Abstract

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Oxford: 66:67:311:861.0. **Keywords:** Chipping machines, pulp chips, pulpwood logs, logging economics, logging operations.

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APPENDIX

Table 4. — Man and machine rates used in computing costs

Function	Rate Used
Falling, limbing and bucking	Arizona costs are based on Southwest Forest Industries, Inc. records. $7.00 per hour for chainsaw and operator for Colorado.
Skidding	Arizona costs are based on Southwest Forest Industries, Inc. records. $17.10 per hour for skidder, operator, and choker setter on the spruce-fir area in Colorado; $17.96 per hour for reskidder and operator
Loading pulpwood	$37.03 per hour for loader man, operator, and assistant loader man.
Hauling pulpwood	$0.12 per loaded mile per unit
Rail haul	Contract rate of $3.53 per unit, McNary to Snowflake
Slashing	$7.12 per unit based on past records
Chipping	$53.84 per hour for inwoods debarker-chipper, operator and helper $17.68 per hour for front-end loader and operator $3.20 per unit for chipping at the mill based on past records
Truck haul chips	Rates computed
Rail haul chips	Contract rate of $7.89 per unit, Gallup, N.M. to Snowflake
Reload chips on rail	$0.40 per unit estimate
Scaling and reloading chips at mill	$0.40 per unit
Scaling, unloading pulpwood at mill	$0.75 per unit

Table 5 — Cost determinations for the Nicholson "Logger" Model Utilizer

Investment Estimate	
Logger Utilizer	$200,000.00
Freight (Seattle to Springerville)	2,896.00
Spare Parts Inventory	4,000.00
Local Taxes	7,140.00
Total	$214,036.00
Fixed Costs	
Materials	
Service Truck ($6,000÷6)	$1,000.00
Tools ($3,300÷6)	550.00
Other	
Office (supplies, phone, etc.)	350.00
Insurance (1% of average value)	1,000.00
Taxes (200,000 x .25 @ $6.3294 per $100)	3,165.00
Depreciation	35,673.00
Interest (6% add on for initial investment)	12,842.00
Pre-startup and training ($1,200÷6)	200.00
Total Fixed Cost/Year	$54,780.00
Fixed Costs/Hour (Total÷1600 hrs.)	$34.24
Variable Costs	
Labor — Operating (42 weeks x 40 hours/week)	
Operator ($5.53/hour x 1680)	$ 9,290.00
Helper ($4.13/hour x 1680)	6,938.00
Labor — Maintenance (9 hours/week performed by both operator and helper at 1½ times normal rate)	5,216.00
Parts and Supplies	
Equipment ($0.25/unit x 63 units/day x 200 days)	3,150.00
Diesel Engines ($0.60/hour x 1600 hours)	960.00
Diesel Fuel (14.5 gals/hr. at $0.25/gal. — machine running time/day x 14.5 x $0.25 x 200)	5,800.00
Total Variable Costs/Year	$31,354.00
Variable Cost/Hour (Total÷1600 hrs.)	$19.60
Total Utilizer Costs	
Owning Cost/Hour	$34.24
Variable Operating Cost/Hour	19.60
Total Utilizer Cost/Hour	$53.84
Front-end Loader	
Owning Cost/Hour	$ 6.78
Variable Operating Cost/Hour	10.90
Total Loader Cost/Hour	$ 17.68
Total Hourly Cost of Operating Utilizer System	71.52
Total Cost of Operating Utilizer System/8-hour Day	572.16

Specifications and Features of the "Logger" Model Utilizer

General Characteristics

The Utilizer consists of two units, each of which has a standard fifth-wheel hookup for a highway tractor. Both units are of legal highway size and weight. The two units couple together for the debarking-chipping operation, and can be moved coupled together off the highway where roads are relatively straight. Maximum log diameter that can be processed is 18 inches. Minimum diameter that can be debarked is about 3 inches. Any length from 6 feet to tree length can be handled. Logs shorter than 6 feet generally will not feed through the tandem hold downs on the debarker.

Specifications

Loader: Nicholson hydraulic heel boom, with cab equipped for complete plant control, except for circuit-breaker panel.

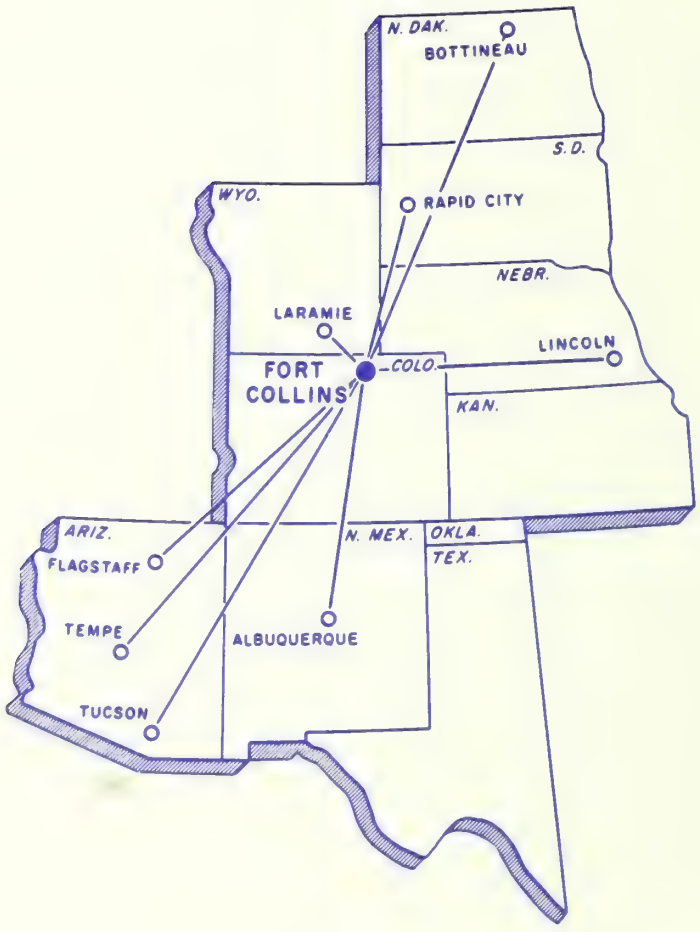
Debarker: Nicholson design 18-inch ring debarker, fully automatic, supplied with tandem hold-down rolls controlled by photo-electric cells. A Nicholson 18-inch-wide belt conveyor can discharge bark to either side of the machine.

Chipper: Nicholson 18-inch V drum overhead-discharge 6-knife model.

Feed Rate: Feed rate is 115 feet per minute for ⅞-inch chips, 100 feet per minute for ¾-inch chips, and 85 feet per minute for ⅝-inch chips.

Engines: A Cummins 903 Diesel with a Clark 16.1 torque converter was used in the field test to power the chipper and log feed. A Caterpillar D330 Diesel Generator Set provided electric power for all other functions. Diesel fuel consumption for both engines is about 14.5 gallons per hour.

Length and Weight of Units: The unit containing the generator set and loader is 8 feet wide, 40 feet long, 13.5 feet high, and weighs approximately 40,000 pounds. The debarking-chipping unit is 8 feet wide, 34 feet long, 13.5 feet high, and weighs approximately 45,000 pounds. With units coupled together, overall length is about 70 feet.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CHAPARRAL CONVERSION POTENTIAL IN ARIZONA

Part I: Water Yield Response and Effects on Other Resources

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by Alden R. Hibbert, Edwin A. Davis, and David G. Scholl

USDA Forest Service
Research Paper RM-126

July 1974

Rocky Mountain Forest and Range Experiment Station

Forest Service

U.S. Department of Agriculture

Fort Collins, Colorado

Abstract

On areas favorable for treatment, conversion to grass reduces fire hazard and substantially increases water yield and forage for livestock. If treatment areas are kept small and interspersed with native chaparral, protective cover and browse for game animals will always be available nearby, and the edge effect created by the openings will enhance the overall environment for wildlife. Chaparral control methods that have proved effective in Arizona are rootplowing, prescribed burning, chemicals, and chemicals in combination with the others. Stream water from treated watersheds shows moderate to low contamination by herbicides. Over the long run, conversion should reduce erosion by reducing or eliminating the heavy erosion cycle set off by periodic wildfires in unmanaged chaparral.

Keywords: Watershed management, chaparral, brush control, water yield improvement, soil erosion, sediment yield, habitat improvement.

USDA Forest Service
Research Paper RM-126

July 1974

CHAPARRAL CONVERSION POTENTIAL IN ARIZONA
Part I: Water Yield Response and Effects on Other Resources

by
Alden R. Hibbert, Principal Hydrologist,
Edwin A. Davis, Principal Plant Physiologist,
and
David G. Scholl, Soil Scientist
Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters maintained at Fort Collins, in cooperation with Colorado State University; authors are located at Tempe, in cooperation with Arizona State University.*

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CHAPARRAL CONVERSION POTENTIAL IN ARIZONA

Part I: Water Yield Response and Effects on Other Resources

Alden R. Hibbert, Edwin A. Davis, and David G. Scholl

INTRODUCTION

In the wake of concern over a dwindling water supply in central Arizona, conversion of chaparral to grass has been advocated by some as a means to augment streamflow. Early research efforts by the USDA Forest Service aimed primarily at grazing and erosion problems were expanded in the 1950's to study the feasibility of increasing water yield in this manner. Effects of conversion on other resources were also evaluated. Part I of this publication reports research activities to increase water yield, and the effects of treatment on erosion, wildlife, and forage production. Part II, a separate paper by Brown et al. (1974), further evaluates the impact of conversion on fire hazard, recreation, and esthetics, and utilizes these findings in an economic analysis of converting chaparral on National Forest land in the Salt-Verde Basin, Arizona.

Experimental conversions on small brush-covered watersheds have substantially increased water yield and forage production for livestock and game animals. Control of wildfire is eased by breaking up large, continuous expanses of heavy brush. Conversion changes the wildlife habitat, favorably for some species, unfavorably for others. Although conversion activities may temporarily increase erosion, the long-term rate should decrease if further soil disturbance is minimized. Burning and chemical control of brush usually leave an esthetically unpleasant appearance for several years until shrub skeletons deteriorate and replacement cover is well established. Proper blending of treated with untreated areas increases the edge effect and creates a mosaic or savanna appearance that can be both esthetically pleasing and productive of game and wildlife.

Research and management must develop sound, efficient, and safe prescriptions for converting chaparral. Much research has been done in shrub control and water yield determinations. More work is needed on methods of establishing and maintaining replacement cover, predicting response to treatment, and safeguarding against long-term degradation of the environment.

RESEARCH BACKGROUND

Chaparral received early attention in California, where shrub species are similar but management problems are more acute than in Arizona. By the late 1800's it was apparent to some that burning or clearing brush in the San Gabriel Valley increased flows and accelerated flood damage (Robinson 1946). The effect of wildfire on streamflow was first documented by Hoyt and Troxell in 1934. They found that wildfire caused the average annual flow on Fish Creek near Monrovia to increase 29 percent or 1.55 inches. While the erosion caused by the increased flows after the fire did not particularly disrupt onsite watershed resources, the deposition of eroded material downstream on agricultural lands and transportation rights-of-way was materially damaging. They concluded that the water user and land manager must weigh the benefits of the extra water against the cost of damages downstream to determine management alternatives for brush lands in water-short areas.

These findings only intensified the controversy surrounding brush burning in California. Livestock interests had long advocated controlled burning to enhance forage production and restrict further expansion of brush into grasslands. Now they were being supported by water interests, at least as long as the water remained "usable" and did not come as destructive floods and mud flows. The extent of the controversy and the general state of knowledge were well summarized in a 1947 report by Adams, Ewing, and Huberty.

As more research was done on the plant-soil-water relations in the chaparral and woodland types (Veihmeyer 1953, Burgy 1958, Rowe and Reimann 1961, Merriam 1961, Lewis 1968), two important facts became clear. First, streamflow and seepage to ground water increase when these cover types are converted to grass. Second, the loss of soil stability caused by conversion — whether by burning or other means — presents the immediate threat of floods and debris flows, particularly on the steep, unstable slopes of southern California brushlands.

In Arizona, research aimed specifically at improving water yield did not begin until the 1950's. Earlier studies by the USDA Forest Service were focused on plant-soil-water relations and on the influence of grazing on runoff and erosion. Range improvement studies were started in various locations in the Salt River drainage in 1921. The Summit plots near Globe were established in 1925 (Rich 1961), and in 1932, the Sierra Ancha Experimental Forest near Roosevelt Lake was set aside for watershed research (USDA Forest Service 1953; Pase and Johnson 1968).

These early research efforts established many of the basic concepts and the functional relationships between climate, plants, soils, and land use which are now taken for granted. Much of the basic hydrology of the Salt River watershed was described by Cooperrider and Sykes in 1938. While some revision and modification has been necessary in the face of recent findings, the bulk of their report is as valid today as it was in the 1930's. In summarizing their report, Cooperrider and Sykes stressed that, although water yield might conceivably be increased by changing the vegetation, it was as yet unproved as a practical means of improving water supply. Their greatest concern was the ultimate deterioration of the soils resulting from overgrazing, fire, or other methods of reducing the cover. Although flooding and debris flows were less severe than in southern California, they feared that treatment would increase surface runoff and erosion, and that reservoirs would fill with sediment to intolerable levels. This concern is less valid today. We have found that water yield can be improved without unduly accelerating erosion if care is taken in the conversion process. However, there is little cause for complacency; the erosion rate must be further reduced if the effectiveness of storage systems is to be preserved.

Concern over the water situation intensified as runoff from central Arizona watersheds continued to decline through the 1940's and 1950's. While some attribute the decline to an increase in brush and trees following decades of overgrazing and fire protection (Wingfield 1955, Warskow et al. 1969), others cite a concurrent decline in precipitation as the major cause (Barr 1956, McDonald 1960). In any event the demand for water has long exceeded the surface supply, and about 4 million acre-ft is being "mined" each year from ground water. Of the estimated 80 million acre-ft of rain and snow received each year by Arizona, only about 2 million acre-ft or 2½ percent is yielded as streamflow (Harshbarger et al. 1966). Since transpiration by vegetation, much of it considered to be nonbeneficial, requires so much water, ways were considered to reduce this use and increase water available for other higher priority uses.

The demand for water by agriculture provided the impetus for a concerted effort by watershed specialists to evaluate the feasibility of increasing water yield on Arizona's major water-producing area, the Salt-Verde drainage above Phoenix. Their consensus was published as the Barr Report (Barr 1956). Limited experience in various parts of the country at that time indicated that converting forest cover to grass could increase water yield. Even less was known of the water potential in brushlands, although the studies in California were providing some positive results. As part of the Arizona Watershed Program, several experimental watersheds were established on National Forest lands to evaluate effects of manipulating vegetation, primarily for improving water yield. Only the studies conducted by the Forest Service in the chaparral will be discussed here. Other studies were made in juniper, pine, mixed conifer, and riparian vegetation by the Forest Service and other agencies.

Of the several vegetation types considered for treatment in the Barr Report, chaparral was given low priority because little improvement in water yield was thought possible on these sites. However, our studies have since shown strong water yield increases after chaparral conversion. On the other hand, conversions in the juniper type have shown little promise of increasing water yield (Brown 1971). It appears now that the chaparral potential was misjudged because its precipitation was generally underestimated. Precipitation in the chaparral was estimated in the Barr Report to vary between 14 and 18 inches; we now know that most of the chaparral gets more than 18 inches.

VEGETATION, SOIL, AND WATER RELATIONS

Vegetation

Chaparral in Arizona occurs mostly on rough, broken country south of the Mogollon Rim, extending generally in a discontinuous band across the central part of the State from northwest to southeast (fig. 1). The type occurs at elevations ranging from 3,000 to over 6,000 ft, depending on exposure, soils, and climate (fig. 2). The most extensive and continuous chaparral stands are found on or adjacent to the Prescott and Tonto National Forests, and on Indian lands in the Salt River basin. The upper margin of the chaparral borders ponderosa pine or occasionally pinyon-juniper stands, while the

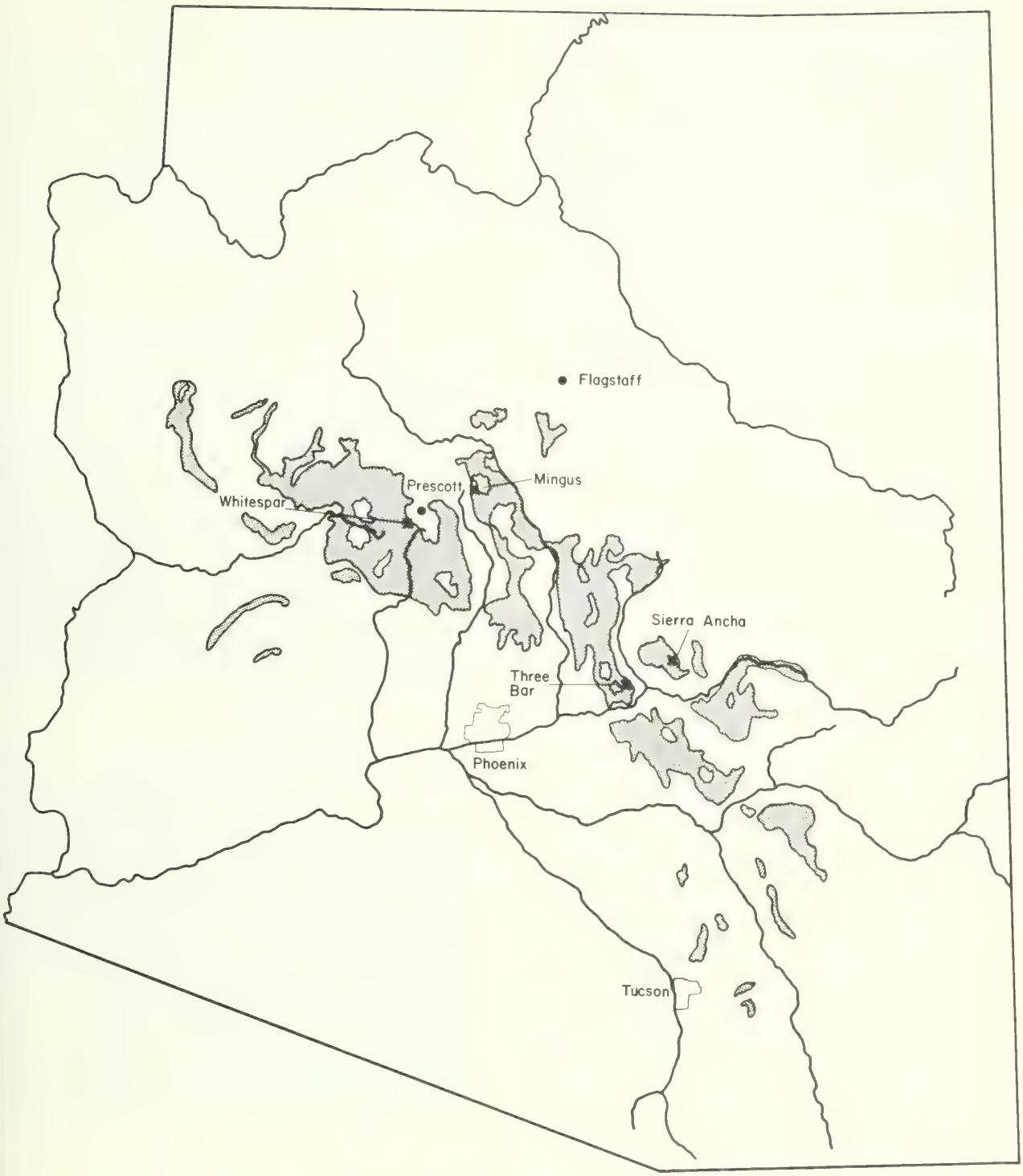


Figure 1. — Distribution of chaparral (Brown 1973) and location of experimental watersheds in Arizona.

Figure 2. — Mixed chaparral dominated by shrub live oak and true mountainmahogany on deeply weathered diabase soil at 5,000 ft elevation and 25 inches precipitation (Sierra Ancha Experimental Forest).

lower margin borders semidesert grassland or southern desert shrub. In southeastern Arizona, chaparral mixed with oak-woodland adjoins ponderosa pine on the flanks of a few isolated desert mountain ranges such as the Santa Catalinas (Lowe 1964).

The area covered by chaparral has been estimated as large as 8 percent (5.8 million acres) of the land area of Arizona by Nichol (1952). However, more recent surveys indicate less acreage. Spencer (1966), using USDA Forest Service survey techniques, estimated 3.7 million acres. A smaller acreage, 3.2 million acres, was determined by measuring chaparral areas shown on vegetation maps published by the University of Arizona (Humphrey 1963) and by the Arizona Resources Information System (Brown 1973). These differences in area, particularly between Nichol and the more recent surveys, reflect lack of common criteria for classifying chaparral. Both Nichol and Spencer include as chaparral extensive areas in the Southeast that are classified as woodland or encinal by Humphrey and Brown. Also, the lower margin of the chaparral type is so indistinct that many thousands of acres might be classified as either chaparral or desert shrub, depending on individual interpretation of species composition and cover density.

Since the more recent estimates are probably the most accurate, it is probable that chaparral covers considerably less than 4 million acres in Arizona. Of this acreage, a large proportion cannot be considered for treatment because it is classified as wilderness, it is too steep, its cover is too sparse, or for other reasons it is not suitable for conversion. These restrictions are discussed further in Part II in an economic analysis of conversion.

The chaparral community typically consists of moderately deep to deep-rooted, evergreen sclerophyllous shrubs that reach best development on deep soils or on deeply weathered or broken rock mantles (fig. 3). Most chaparral shrub species are prolific crown and/or root sprouters, and produce few seedlings (Pase 1969); the few nonsprouters produce abundant seed. The sprouting species live to considerable age; Pond (1971) found little change in individual plants after 47 years.

A

B

Figure 3. — A, Dense mixed chaparral, primarily Emory oak and Pringle manzanita, on deeply weathered granite soil at 6,000 ft elevation and greater than 25 inches precipitation (Tonto National Forest).
B, Medium to low density chaparral dominated by shrub live oak and hairy mountainmahogany on deeply weathered sedimentary rock at 6,000 ft elevation and 18 inches precipitation (Prescott National Forest).

The type is well adapted to fire. Because the well-developed root systems can exploit the moisture and nutrients in a large volume of soil, stands regenerate rapidly following fire (Pond and Cable 1962, Pase and Pond 1964, Pase and Lindenmuth 1971). Favorable weather conditions germinate seeds of nonsprouting shrubs, such as *Ceanothus* and *Arctostaphylos* species, which benefit from heat scarification. Such seeds may lie dormant in the soil for many years before the conditions necessary for germination occur (Pase 1965).

Shrub crown cover may vary from open (less than 40 percent) on xeric sites to dense (more than 60 percent) on favorable sites where moisture is less limiting. Under dense brush, herbaceous cover is virtually absent. Annual litter production was measured at 1 ton per acre under stands dominated by oak and mountain-mahogany (Pase 1972). Forest floor weights of more than 20 tons per acre were found under dense manzanita stands in central Arizona (Glendening and Pase 1964). Even greater accumulations may be possible; in southern California, Kittredge (1955) reported forest floor weights under chaparral of up to 50 tons per acre.

Compared with other vegetation types, the chaparral community consists of a relatively large number of species of diverse habit, usually dominated by one or more of the following species: shrub live oak (*Quercus turbinella* Greene), Palmer oak (*Q. chrysolepis* var. *palmeri* (Engelm.) Sarg.), Emory oak (*Q. emoryi* Torr.), birchleaf and true mountainmahogany (*Cercocarpus betuloides* Nutt. and *C. montanus* Raf.), pointleaf and Pringle manzanita (*Arctostaphylos pungens* H.B.K. and *A. pringlei* Parry), Wright and yellowleaf silktassel (*Garrya wrightii* Torr. and *G. flavescens* Wats.), desert ceanothus (*Ceanothus greggi* Gray), sugar sumac (*Rhus ovata* Wats.), skunkbush (*R. trilobata* Nutt.), hollyleaf buckthorn (*Rhamnus crocea* Nutt.), and Yerba-santa (*Eriodictyon angustifolium* Nutt.).

Where shrub canopy is open to moderately dense, grasses and forbs may be abundant in the intershrub spaces. Common grasses are sideoats and hairy grama (*Bouteloua curtipendula* (Michx.) Torr. and *B. hirsuta* Lag.), three-awns (*Aristida* spp.), cane bluestem (*Andropogon barbinoidis* Lag.), plains lovegrass (*Eragrostis intermedia* Hitchc.), green sprangletop (*Leptochloa dubia* (H.B.K.) Nees), wolftail (*Lycurus phleoides* H.B.K.,) and muhlys (*Muhlenbergia* spp.). Spring- and summer-growing annuals, abundant in favorable wet years, include red brome (*Bromus rubens* L.), witchgrass (*Panicum capillare* L.) and needle grama (*Bouteloua aristidoides* (H.B.K.) Griseb.). Common forbs include penstemon (*Penstemon* spp.), redstar morningglory (*Ipomoea coccinea* L.), dark spurge (*Euphorbia melanadenia* (Pursh) Britt. & Rusby), and bluedicks (*Dichelostemma pulchellum* (Salisb.) Heller). Common halfshrubs include Wright buckwheat (*Eriogonum wrightii* Torr.), broom snakeweed (*Gutierrezia sarothrae* (Pursh) Britt. & Rusby), and rough menodora (*Menodora scabra* Gray).

While generally classed as forest, the chaparral type is considered noncommercial because little or no timber and wood products are produced. However, it is important habitat for several big game species, including mule and white-tailed deer and black bear. Water production is intermediate between the very low-producing desert areas below and the better-watered forest areas above. Forage for domestic livestock is fair in open chaparral but is sparse in dense stands of brush.

In general, as density of the shrubs increases, useful production declines, fire hazard and cost of control increases to high levels, and accessibility is severely restricted. Because of these features, the chaparral is somewhat unique in that most management practices that reduce stand density tend to improve productivity and accessibility.

Climate

The climate of central Arizona is marked by two rather distinct wet periods. Winters are cool and wet through March, followed by warm, dry weather for 2 or 3 months until summer rains start in July. Dry weather usually returns by October and persists until winter rains begin in November or December. Since most of the chaparral is located in the central part of the State, the discussion of climate and hydrology will be restricted to this area.

Mean annual precipitation ranges from about 16 inches at the lower limits of the chaparral to over 25 inches on the wetter sites. Precipitation generally increases with elevation, but not uniformly so; elevation of itself is not a good indicator of precipitation. The proximity of mountains and other physiographic factors that control flow and cooling of air combine with elevation to produce the local climate. Some snow falls each year, but normally snow is not an important factor in the hydrology of the chaparral type.

Roughly 55 percent of the annual precipitation falls as rain or snow between November and April. The moisture usually comes from the Pacific as frontal-type storms which become heavier as the moist air is forced over the central highlands. These storms may dump several inches of water in 24 hours, but their intensity is relatively low. Summer moisture from the Gulf

of Mexico in the form of local convection storms accounts for about 35 percent of the annual rainfall during July, August, and September. These storms are often intense and erratic, dropping as much as 3 inches of water in an hour. The remaining 10 percent of annual rainfall comes in May, June, and October, the driest months. The water year is calculated from the first of July to coincide with the end of a 2- or 3-month period of low hydrologic activity when the moisture regime varies the least from year to year.

Precipitation varies greatly in Arizona, both in space and time (McDonald 1960). Temporal variability is usually the most important in an arid environment because seasonal and annual extremes in rainfall, particularly on the dry side, profoundly affect the vegetation and the amount of water produced. Spatial variability, or differences in areal distribution of precipitation, presents less of a problem because land use and management practices can be more easily tailored to accommodate differences between sites than between years.

Mean annual precipitation is commonly used to describe the moisture regime of an area. In itself, however, the mean tells nothing about the frequency and seasonal distribution of rain, and little about the magnitude of dry and wet years, critical factors in the survival and maintenance of plant cover. Long-term records are scarce in the chaparral but available data suggest that the driest years receive about one-half the mean precipitation while the wettest years get about double the mean. Thus, in some marginal areas, as little as 8 inches of rain may fall in dry years while in very wet years the wetter sites might receive as much as 50 inches.

Arizona is also noted for its wide range in temperature, which is closely related to elevation (Smith 1945). Mean temperature is determined by averaging daily maximum and minimum readings. Within the chaparral zone, mean annual temperatures range between 50° and 65° F. Mean monthly temperatures may vary from less than 40° in January to more than 80° F in July.

Wind generally is out of the southwest. Average windspeed at 6 ft above the ground, about the height of the shrub canopy, varied from 30 to 112 miles per day over a 2-year period at four chaparral sites in central Arizona. At present we do not know the quantitative effect of wind on ET (evapotranspiration) on these sites, but it may be an important factor in the water balance. Potential ET is much greater than precipitation in the chaparral. Estimates vary between 45 and 60 inches, depending on climatic and physiographic factors. Class A pan evaporation averaged 74 inches per year at 5,100 ft elevation (Sierra Ancha Experimental Forest), and about 82 inches at 3,500 ft (Three Bar watersheds).

Soil, Geology, and Cover Relations

Soils supporting chaparral have certain characteristic properties throughout central Arizona. Typically, soils are deep, coarse textured, and poorly developed. Soil as used here includes all porous material (regolith) in which weathering and roots are active. The distinction between soil depth and solum depth (A and B horizons) is critical in this case, since most of the soil is in the C horizon. Soil surveys which describe the soil as shallow generally pertain to solum depth. Usually, the A horizon is only a few inches thick, and the B horizon is commonly absent. Soil texture varies from cobbly and gravelly loamy sand to gravelly loam.

Parent materials include deeply weathered and fractured granite, schist, diabase, and sandstone. Granites are found on more than half the total chaparral area, while diabase and sandstone comprise less than 10 percent. At the Three Bar experimental watersheds (figs. 1 and 4), coarse-grained granite was found by seismic exploration to be weathered and fractured 20 to 40 ft deep (Ackermann and Walters 1965). Roots of the dominant chaparral species penetrate these materials to as much as 30 ft, although the majority of roots are concentrated in the upper few feet of soil and in the numerous fractures cutting through the decomposing rock.

The C horizon is hydrologically important, even though total porosity may be only 20 to 25 percent. Because of deep weathering, this zone stores much winter rain, which the deep-rooted shrubs use during dry periods.

Figure 4. — Three Bar experimental watersheds west of Roosevelt Lake on Tonto National Forest.

Chaparral shrubs grow on a variety of geologic rock types, all of which weather to produce a deep, coarse regolith. In contrast, rock types such as basalt, limestone, and quartzite, which weather to relatively fine-textured shallow regoliths, normally do not support chaparral, even though rainfall and elevation are similar. These soils usually support juniper, pinyon, or grass. On the Sierra Ancha Experimental Forest, for example, shallow quartzite soils support grass with scattered shrubs, while adjacent soils derived from intrusive diabase support a medium-dense stand of brush. Other examples of brush on granite next to juniper on basalt can be found on the Tonto and Prescott National Forests.

The view that the distribution of these two vegetation types (chaparral and juniper) is more a function of soil than of climate and elevation has not been widely held. Juniper has traditionally been thought of as occurring at higher elevation and at an assumed higher rainfall zone than chaparral; the rainfall assumption, however, is not valid.

As an example, Utah juniper and alligator juniper stands dominate the central portion of the Beaver Creek drainage south of Flagstaff at elevations ranging from 5,000 to 6,500 ft where annual precipitation averages 18 to 20 inches. On the Mingus watersheds 30 miles to the west at similar elevation and precipitation, the dominant vegetation is chaparral with scattered juniper and pinyon trees. Soil is the only apparent difference in the sites that would account for the difference in vegetation. The soils on Beaver Creek are derived from basalt and are relatively fine textured and shallow, compared with the soils on Mingus which are derived from Precambrian sedimentary rock that is shattered and weathered to a greater depth. Farther to the southwest on the Whitespar watersheds, again at 6,500 ft, the chaparral is even better expressed on granite-derived soils, which appear to be somewhat deeper than at Mingus. Here precipitation is 22 to 24 inches, and brush gives way to ponderosa pine on the higher, more moist sites.

Water Relations

Streamflow

There are no large watersheds covered solely by brush. Since the environment for chaparral is favorable mainly along flanks of mountain ranges, most large drainages cross these "bands," extending into conifer above or semidesert below. Catchment areas lying entirely within the chaparral seldom exceed a few thousand acres.

Figure 5. — Streamflow gages on Whitespar B experimental watershed, Prescott National Forest. Medium to low flows are measured by the sharp-crested 120° V-notch weir; flood flows by the San Dimas flume.

Streamflow has been gaged (fig. 5) by the USDA Forest Service, and USDI Geological Survey on a number of small experimental watersheds ranging in size from 9 to about 3,000 acres. Mean annual water yield on these small watersheds varies from less than 0.1 inch per year on the drier sites to 2.5 inches on the wetter areas. An overall average yield for the brush type is difficult to ascertain from these data because the catchments are not necessarily representative of all of the chaparral in Arizona. By selecting data we consider most representative, we estimate mean yield to be 1.25 inches based on 22 inches of mean precipitation. This compares with earlier estimates of water yield in Arizona chaparral of 0.5 inch (Barr 1956) to 1.5 inches (U.S. Senate 1960).

Some of the water yielded by small headwater catchments is lost to riparian vegetation downstream, the proportion being larger in dry years than in wet years. The amount of the loss will vary according to length and type of stream course. Many of the intermediate-size watersheds, such as 119,000-acre Sycamore Creek near Fort McDowell, flow intermittently on the surface, although flow may continue in the channel alluvium. Surface flow in the upper part of Sycamore Creek is perennial, but in the lower part all surface flows up to about 200 ft^3/s (cubic feet per second) soak into the unconsolidated channel fill, which along the lower 9 miles is as much as 100 ft deep. Thomsen and Schumann (1968) estimate that some 4,000 acre-ft per year discharges to the Verde River through this alluvium.

The amount and seasonal distribution of streamflow depends largely on when and how much it rains. Most of the water is produced

during the cool winter months when ET is low and precipitation is relatively heavy. Despite high intensities, very little of the summer rainfall runs off. The proportion intercepted by the brush is larger because rains are smaller. That reaching the ground is absorbed readily in the upper few inches of soil, where it is quickly transpired or evaporated. Headwater streams often are dry by early summer, although recurrent heavy rains may sustain base flow at a low level throughout the summer.

The average seasonal distribution of yield from the four experimental sites in the chaparral is 85 percent in the November-April dormant season when 55 percent of the precipitation occurs, and 12 percent in July, August, and September with 35 percent of the rain (fig. 6). The three driest months (May, June, and October) account for the remaining 3 percent of the yield from 10 percent of the rain. In the Sycamore Creek drainage, Thomsen and Schumann (1968) found a similar seasonal distribution: The November-April period accounted for about 60 percent of the precipitation, but was responsible for 90 percent of the yield.

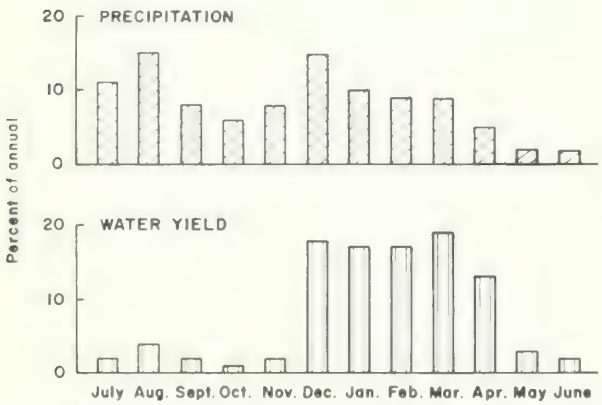


Figure 6. — Mean monthly precipitation and water yield as percent of annual (average of four experimental sites in the chaparral).

Annual streamflow in the chaparral fluctuates even more widely than precipitation. In dry years, water yield may be negligible or even absent. In fact, in a very dry situation a condition develops that can be thought of as "negative yield" in the sense that water deficits continue to increase after streamflow stops. Before streamflow (base flow) can resume, this deficit must be satisfied. Thus after prolonged drought (such as the winters of 1970-71 and 1971-72), a greater amount of recharge is necessary to attain a given flow level than in years with rainfall near normal.

While dry years produce little water, wet years, particularly wet winters, may yield 20 percent of precipitation or more in some areas. One wet year may produce runoff equal to several years of near-average precipitation. This relationship and its implications for improving water yield are discussed further in the section on water yield increases.

Plant-Water Relations

Chaparral occupies zones that are too dry for forests, yet receive sufficient rainfall to allow grass or deep-rooted woody plants to thrive. Water is the major limiting factor for plant growth; the deep rooting habit of chaparral shrubs enables them to survive periodic seasonal droughts. Both climate and vegetation in the chaparral favor large ET losses. Because ET accounts for such a large proportion of precipitation, water yield might be considerably improved if transpiration can be reduced. It is worthwhile, therefore, to consider some of the plant-water and soil-water relationships that would be modified by chaparral conversion.

Climate, aspect, plant, and soil affect ET. Climatic factors are precipitation, solar radiation, temperature, humidity, and wind. Aspect of the site influences the local climate, particularly solar radiation and temperature. The plant influences transpiration by its crown, leaf, and root characteristics, and by stomatal opening. Soil depth, texture, and permeability affect the supply and delivery of water to the plant roots. Since chaparral conversion involves changes in the plant cover, the factors of most importance are those associated with plant and soil.

The two rainy seasons in Arizona, combined with the broadleaved evergreen character of chaparral shrubs, present an interesting hydrologic situation. Because the shrubs are foliated year-round, they can transpire whenever atmospheric and soil conditions are favorable. The soil is recharged in the winter when precipitation is heaviest. Some winter transpiration undoubtedly occurs, although the rate is low because of cool temperatures. Summer rains break a long drought which lasts from early spring to midsummer. During this prolonged dry period, atmospheric conditions are favorable for high ET losses, and the soil moisture reserve is depleted. Summer rains seldom are concentrated enough to recharge the soil, although the moisture is important for plant growth. Any water in excess of immediate plant demands is drawn on during the dry fall months when the ET potential is still high. Consequently, early winter rains are utilized to recharge the soil mantle that dried in the preceding months.

Water availability to chaparral plants depends first on the water supply, and then on the amount of storage and depth of rooting in the soil. When the soil is only a few feet deep, the type of vegetation should not appreciably influence water yield unless there is a difference in length of season of water use or in transpiration rate. Short-lived annuals, for example, would be expected to use less water than perennials.

In deep, well-drained soils, the type of vegetation markedly affects water yield. Deep-rooted shrubs whose roots ramify the entire soil mantle can deplete the soil-water reserve to a greater extent than shallow-rooted grasses and forbs. Even the various shrub species may differ significantly. Other factors probably contribute as well. Interception of precipitation by brush is greater than by grass (Corbett and Crouse 1968); thus more water enters the soil under grass. Also, seasonal dormancy of grass, particularly during winter, results in less water withdrawal, and greater recharge below the grass rooting depth. Still other factors such as albedo, leaf structure, and stomatal behavior may cause water use by grass to be less, but most of the water savings are believed to result from water being less available to the shallow roots.

BRUSH CONTROL AND ESTABLISHMENT OF REPLACEMENT COVER

The eradication or suppression of brush is basic to chaparral conversions for improving water yield. Under natural conditions chaparral is well adapted, and will not be permanently reduced unless some form of brush control is practiced. Economical methods are available for controlling chaparral in some situations, but in many cases methods are either ineffective or too expensive for widespread use. Another problem is that no existing brush control herbicide is fully registered for use on watersheds (see the Pesticide Precaution Statement at the end of this report). Nor is the fate of the phenoxy herbicides clear at the present time.

A major challenge in chaparral control is the development of treatment prescriptions which are effective, economical, and safe to humans, wildlife, livestock, and aquatic life. Contamination of the watershed ecosystem (particularly stream water) with herbicides, or undesirable alterations of the nutrient composition of stream water as a byproduct of brush control, are hazards which must be seriously considered.

Chaparral control methods which have proved effective in Arizona include prescribed burning, mechanical methods, chemicals, and prescribed burning followed by chemicals. Many of the techniques used in southern California (Bentley 1967) may be applied here. However, California chaparral differs in species composition and summer moisture. Establishing perennial grass cover in central Arizona is enhanced by summer rains which account for about one-third of the annual precipitation.

Prescribed Burning

Prescribed burning (fig. 7) modifies the density, stature, and composition of chaparral. One advantage of fire is that the environmental changes it creates were also common in the evolution of the ecosystem. A disadvantage for most chaparral areas is that control is temporary. Therefore the objective must be suppression rather than eradication.

Figure 7. — Firing chaparral with hand-held torch during prescribed fall burning on Sierra Ancha Experimental Forest.

Not all chaparral shrubs respond similarly to burning (table 1). A fire-tolerant plant is one that rapidly recovers by sprouting even after repeated burns; a fire-susceptible plant does not sprout after its top is killed by fire, although fire may stimulate its seeds to germinate. Consequently, the site can be reoccupied by seedlings of the same species or by other species whose seeds were stored in the ground or carried in after the fire. A moderately fire-tolerant plant can be controlled by a limited number of burns 1 or 2 years apart. Shrub live oak, a fire-tolerant species, has an enormous sprouting capacity; in one test it survived six annual burns (Pond and Cable 1960). Manzanita, on the other hand, is fire susceptible.

Table 1.--Susceptibility of some Arizona chaparral shrubs to fire and low-volatile esters of phenoxy herbicides (brush killer [2,4,-D + 2,4,5-T], 2,4,5-T, or silvex)

Botanical and common names of shrubs	Susceptibility to-- Fire	Phenoxy herbicides	Remarks
Acacia greggii catclaw acacia	Tolerant[1]	Mod. resistant	Refoliates and/or resprouts from base
Arctostaphylos pringlei Pringle manzanita	Susceptible	Mod. susceptible	Spray when actively growing; nonsprouting
Arctostaphylos pungens pointleaf manzanita	Susceptible	Mod. susceptible	Do.
Berberis haematocarpa barberry	--	Susceptible	
Ceanothus greggii desert ceanothus	Susceptible	Susceptible	
Ceanothus integerrimus deerbrush ceanothus	Susceptible	Susceptible	
Cercocarpus betuloides birchleaf mountainmahogany	Tolerant[1]	Mod. resistant	Refoliates and/or resprouts from base
Cercocarpus breviflorus hairy mountainmahogany	Tolerant[1]	Mod. resistant	Do.
Cercocarpus montanus true mountainmahogany	Tolerant[1]	Mod. susceptible	Do.
Ericdictyon angustifolium yerba-santa	Tolerant[1]	Susceptible	
Garrya flavescens yellowleaf silktassel	Mod. tolerant[1]	Mod. resistant	Do.
Garrya wrightii Wright silktassel	Mod. tolerant	Mod. resistant	Do.
Mimosa biuncifera Wait-a-bit	Tolerant[1]	Mod. resistant	Do.
Quercus chrysolepis var. *palmeri* Palmer oak	Tolerant[1]	Mod. resistant	Do.
Quercus emoryi Emory oak	Tolerant[1]	Mod. resistant	Do.
Quercus turbinella shrub live oak	Tolerant	Mod. resistant	Do.
Rhamnus crocea hollyleaf buckthorn	Mod. tolerant	Mod. resistant	Do.
Rhus ovata sugar sumac	Tolerant[1]	Mod. susceptible	Resprouts from base.
Rhus trilobata skunkbush sumac	Mod. tolerant	Mod. susceptible	Do.

[1]Tentative classification.

Prescribed burning is done during periods of suitable and acceptable fire hazard which will assure the desired control, usually in fall or winter. Chemical sprays can be used to desiccate the brush and increase its flammability (Pase and Lindenmuth 1971), although such sprays may not always be effective or necessary on mature stands. More information and testing are needed to determine how desiccation affects intensity and patterns of burning. Brush can be desiccated with fast-acting contact herbicides such as diquat and toxic weed oils containing pentachlorophenol, or with slow-acting low-volatile esters of 2,4-D or 2,4-D plus 2,4,5-T.

The strategy for prescribed burning depends on the type of chaparral. Dense manzanita can be eradicated by a single burn, although its seeds will usually germinate profusely. If grass can be established before the manzanita seedlings gain dominance and again bear fruit, which requires several years, prescribed grass fires will eliminate the new shrub plants and perpetuate the grass. The oak-mountainmahogany complex includes many sprouting species, but normally is dominated by shrub live oak. A single burn followed by seeding of grass can achieve limited objectives, such as a temporary increase in water yield, forage, and

browse, or the reduction of brush density in critical areas as a precaution against wildfires. However, the sprouting brush rapidly recovers to near prefire conditions, and within a few years the temporary advantages are lost except that the stand will not readily burn again for several years.

Using repeated prescribed burns to kill brush and maintain conversion is sometimes dismissed as impractical because brush sprouts have such a competitive advantage over grass during the first few postfire years. After the first burn of mature brush, subsequent burns depend on an adequate grass cover to carry the fire. Very little research effort has been directed toward improving the method, however, despite its attractiveness as an alternative to the use of herbicides. Its success depends on rapid establishment of a grass cover so that a repeat burn fueled by grass is possible before the brush sprouts gain dominance over the grass.

Prescribed burning could be improved in several ways. Chaparral is normally burned during the fall or winter months when the wildfire hazard is low. Grass is established most successfully when the seeds are sown into the ashes soon after fire, but the commonly used lovegrasses germinate best if seeded just before the summer monsoons in late July and August. Perennial grasses are needed which will germinate during the fall and winter months to increase competition against the brush sprouts, and to provide immediate protection for the soil. Techniques are needed for establishing grass on steep slopes and for giving the grass a competitive advantage, perhaps through the use of fertilizers or biological controls such as goats to suppress sprout regrowth. More drought-tolerant and aggressive grasses are also needed. Seeded perennial grasses must be able to survive the effects of repeated burns.

Mechanical Methods

Mechanical equipment used to control brush includes rootplows, bulldozers, and brush crushers and cutters. Terrain is the major obstacle with all heavy equipment. Steep slopes and unusually rocky and gullied land often prohibit their use. Pond (1961) estimates only 2 to 8 percent of the chaparral is suitable for treatment with heavy equipment. Mechanical methods have the greatest potential on relatively level rangeland where forage production is the major objective. Their potential on steep headwater catchments is very limited.

Even on relatively level land, only the rootplow is adequate for eradicating chaparral because it kills the entire plant. Since other methods only reduce the overstory, their usefulness is restricted to preparing brush for burning and for temporary clearing operations such as fuel breaks. The rootplow is mounted behind a heavy tractor equipped with a bulldozer blade (fig. 8). The blade pushes the brush over and the rootplow is drawn 12 to 18 inches beneath the soil surface, severing root crowns from roots and lifting the root crown above ground to dry. The rootplow is limited to slopes less than 20 percent. Rootplow trials in the chaparral of Arizona have been conducted mainly on rangeland where shrub live oak predominates. Shrub mortality is usually 80 percent or more. Surviving shrubs were generally missed by the plow. With careful rootplowing it should be possible to achieve 90 percent or more brush reduction (Pond 1961, Pond et al. 1965).

All of the major shrubs on the low-elevation chaparral ranges can be controlled by the

Figure 8. — Rootplowing on Prescott National Forest. The blade is 12 ft wide and weighs approximately 2 tons. Seed is broadcast from rear of tractor.

rootplow. Yerba-santa, which sprouts from roots, regenerates to some extent if roots remain covered by moist soil. However, it is present in such limited amounts as to be unimportant. Retreatment of some kind may be necessary in manzanita if seedlings reinvade, but thus far reinvasion has not been a problem. Grass is usually seeded during plowing by mounting a seeder on the rear of the tractor.

Chemical Methods

Herbicides, properly used, can perform an important function in controlling chaparral on watershed lands. In large-scale projects greatest reliance has been placed on the phenoxy herbicides. Although when used alone they do not provide adequate control of some of the dominant chaparral shrubs, they have provided the only economical chemical method for treating large areas.

Chemicals Applied to Foliage

The most important of the foliage sprays are the phenoxy group of which 2,4-D (2,4-diclorophenoxyacetic acid), 2,4,5-T (2,4,5-trichlorophenoxyacetic acid), and silvex (2-(2,4,5-trichlorophenoxy)propionic acid) are the most commonly used. 2,4,5-T controls a greater number of species of woody plants than 2,4-D, but some plants are more susceptible to 2,4-D. Because most brush areas are composed of several species, commercial mixtures of 2,4-D and 2,4,5-T, called "brush killers," are commonly used. The dominant woody species in Arizona chaparral are affected most by 2,4,5-T and silvex (Lillie and Davis 1961, Davis 1962a, Lillie 1963). In general, they are about equally effective against shrub live oak.

A variety of formulations of these herbicides is available for brush control: low-volatile esters (propylene glycol butyl ether ester, butoxyethanol ester, and isooctyl ester), water-soluble and oil-soluble amines, and emulsifiable acids. Low-volatile ester formulations are the most effective for spraying brush, but they are more volatile than the other formulations, and may affect susceptible crops. Invert (water-in-oil) emulsions of phenoxy herbicides are particularly useful for minimizing the hazard of spray drift.

Foliage sprays can be applied by aircraft, mechanized ground rigs, or backpack mist blowers. Spraying by aircraft, particularly by helicopter (fig. 9), is the only practical or economical method for treating large watershed areas. Shrub composition, herbicide effectiveness, and cost are considerations in choosing the herbicide for a particular project.

The phenoxy sprays kill leaves and some stems. After the initial "brown-out," which is followed by various degrees of defoliation depending upon species, the bushes refoliate. If stems and branches are severely injured, most species will sprout from basal portions of branches and the root crown. Since a single spray suppresses growth only temporarily, repeat treatments are necessary. Poor penetration of low-volume aerial sprays through dense, mature canopies is partly responsible for limited success in reducing crown density. It is possible to cover top growth of fire sprouts more completely, and young sprouts are more susceptible than hardened woody stems.

For maximum effectiveness, foliage sprays of systemic herbicides must be applied at the proper stage of growth. Brush susceptibility is generally considered greatest after the spring flush of new leaves has reached maximum development, but before the leaves form a thick cuticle and are fully hardened. This stage corresponds to the time when transport of photosynthate to the roots begins. Since systemic herbicides are translocated with photosynthate, there is greater possibility of downward movement of herbicide at this stage. Plants are also most susceptible when growing under optimum conditions. Plants under moisture stress are less affected by herbicides.

Chaparral shrubs of Arizona differ in their susceptibility to phenoxy herbicides (see table 1). None can be classified as totally resistant. Susceptible species can be killed by a single treatment. Moderately susceptible species resprout and are killed by one or two treatments if conditions are optimal. Moderately resistant

Figure 9. — Helicopter applying herbicide spray to 1-year-old shrub sprouts on Three Bar watershed C.

species suffer leaf injury and stem dieback, but either refoliate or resprout from the root crowns; they are not eradicated by three or four annual sprays.

One of the chief advantages of the phenoxy herbicides is that they are selective; they are much more toxic to broadleaved plants than to grasses. Even though the phenoxy herbicides when used alone are inadequate for eradicating Arizona chaparral, repeated treatments can suppress the brush and eliminate some of the susceptible and moderately susceptible species. Unfortunately, the more resistant shrubs comprise the bulk of the brush cover. Substantial shrub mortality cannot realistically be expected until after the fourth or fifth annual applications.

Despite the marginal effectiveness of the phenoxy herbicides, they have nonetheless been used extensively to suppress brush in range and watershed improvement projects. Because of their selectivity and low cost, repeated treatments offer a method of tipping the ecological balance in favor of grass. Superior treatments are definitely needed.

Other chemicals applied to foliage include several substituted benzoic acid herbicides. An extensive survey showed 2,3,6-TBA (2,3,6-trichlorobenzoic acid) and dicamba (2-methoxy-3,6-dichlorobenzoic acid) to be the most effective benzoic acids on shrub live oak (Davis 1962b). Field investigations with foliage sprays of 2,3,6-TBA applied with ground equipment were encouraging (Lillie 1962b), but aerial applications were disappointing and considerably less effective than those with 2,4,5-T (Pase 1967).

Foliage sprays of picloram (4-amino-3,5,6-trichloropicolinic acid) are effective against many but not all chaparral species. To increase effectiveness, formulations containing picloram and 2,4-D are available which broaden the susceptibility spectrum. High-volume leaf-stem sprays have been more effective against resistant oak species than low-volume sprays (Davis 1964). Picloram or picloram-2,4-D sprays have shown little improvement over 2,4,5-T or brush-killer mixtures of 2,4-D and 2,4,5-T.

Soil Treatments

Herbicides in granular, pellet, or tablet form can be broadcast on the soil with aircraft, ground rigs, hand-operated fertilizer spreaders, or by hand. Hand applications are particularly suitable for spot treatment of low-density chaparral, or for selective treatment of brush. The method permits a great deal of diversity in application, and is adaptable to many vegetation management objectives.

From the standpoint of application, soil treatments have several advantages over foliage spraying. The greatest advantage is that water, oil, or other spray additives are unnecessary. Equipment requirements are fewer, and the entire procedure is simpler and more convenient. The problem of drift to nontarget areas is also eliminated.

In terms of plant response, the variability in seasonal susceptibility is not a problem with herbicides absorbed from the soil. The chemical should be applied in January or February when there is a good chance that rainfall will move the herbicide into the soil soon after treatment, in order to minimize possible losses through photodecomposition or volatilization.

Herbicides which are effective as soil treatments against chaparral are fenuron, picloram, karbutylate, and bromacil. Of these, only fenuron has been registered for range use; none is registered for watershed use.

Fenuron (1,1-dimethyl-3-phenylurea) has been used with considerable success against chaparral when applied either as a spot treatment by hand or as a broadcast application from helicopter (Davis and Lillie 1961, Lillie 1962a, Davis and Pase 1969). It is not equally effective against all chaparral shrubs, but fortunately the dominant shrub live oak is one of the most sensitive species (Davis and Pase 1969). Broadcast application rates of 8 to 16 pounds active ingredient (ai) per acre are necessary. Since fenuron is toxic to both grass and brush, broadcast application must not be repeated to avoid damage to newly established grass. Individual bushes or clumps of bushes are effectively treated by scattering fenuron pellets at the rate of 20 pounds (ai) per acre on the ground beneath bushes.

Picloram is herbicidally active either as a soil treatment or as a foliage spray. Although soil treatments are more effective than low-volume sprays against shrub live oak (Davis 1964), the oaks are less susceptible to soil-applied picloram than other chaparral species (Davis and Pase 1969). Spot treatments of 10 pounds (acid equivalent) (ae) per acre are needed to achieve 90 percent or more control of shrub live oak.

An important advantage of picloram is that it is less toxic to grasses than any other potential brush control chemical except for the phenoxy herbicides. Although picloram offers considerable promise for controlling chaparral, it has not been registered for range or watershed use in Arizona, and cannot, therefore, be recommended at this time.

Karbutylate (*m*-(3,3-dimethylureido)-phenyl-*tert*-butylcarbamate) is a new, nonselective, soil-applied chemical which is active against a wide variety of woody plants,

grasses, and forbs. Oak species as well as all other chaparral shrubs are susceptible, some more so than others. Nonsprouting species such as manzanita and ceanothus are particularly sensitive; they respond rapidly to soil treatments as soon as rainfall moves karbutylate into the root zone. Topkill is complete in several weeks. Because sprouting species such as shrub live oak and mountainmahogany go through several cycles of refoliating and/or resprouting it may take 2 to 3 years before they succumb. During this time, top injury is severe, and transpiratory water loss is reduced accordingly. Yellowleaf silktassel is one of the most resistant shrubs, but it is a minor component of mixed chaparral.

Spot treatments and broadcast applications of karbutylate applied at the rate of 20 pounds (ai) per acre give essentially complete brush control in mixed chaparral. It appears that broadcast applications of 8 pounds (ai) per acre will effectively control shrub live oak, but higher rates may be required to eradicate some of the more resistant species.

Karbutylate is persistent in soil. Phytotoxic residues from an application of 20 pounds (ai) per acre may remain in the top 6-inch layer of soil for 3 years or more. Herbicide persistence is desirable for controlling sprouting shrubs but undesirable for establishing a grass replacement cover soon after treatment to prevent soil erosion.

There are several possible ways to circumvent the effect of persistent soil residues of karbutylate on sown grasses. One way is to decrease the dosage of broadcast applications and accept a lower level of brush control. Lower dosages would permit grass to be established sooner. A better way may be to apply karbutylate in the form of large tablets spaced 3 to 6 feet apart. Preliminary evidence indicates that brush can be controlled by broadcast treatments with widely spaced tablets that allow grass to grow in the spaces between tablets. Where hand applications are feasible, the spot treatment of individual bushes and clumps would permit grass establishment in the intershrub spaces.

Karbutylate is not presently registered for range or watershed use. If and when it is, the possibilities for manipulating chaparral vegetation will be improved.

Bromacil (5-bromo-3-*sec*-butyl-6-methyluracil) is a potent, nonselective, soil-applied herbicide that has proved effective for controlling chaparral. Like karbutylate, it is persistent in soil. Phytotoxic residues exist for 3 years or more after applications of 10 pounds (ai) per acre. The problem of establishing grass after treatment, and possible solutions, are the same as those discussed for karbutylate.

Spot treatments of 10 pounds (ai) per acre give nearly complete control of the major oaks (shrub live oak and Emory oak), but only moderate control of mountainmahogany. Hollyleaf buckthorn is resistant. In general, bromacil is more active on chaparral shrubs than fenuron, and is about comparable to karbutylate. It is not presently registered for watershed use.

Prescribed Burning Followed by Chemicals

Prescribed burning with followup chemical treatments is an accepted method for converting brush to grassland. Burning the brush serves three purposes: it eliminates the dense overstory; stimulates the development of sprouts, which are more easily controlled than mature brush by presently used foliage sprays; and prepares a seedbed for sown grass seed. The use of fire in conjunction with spraying of sprouts has been more successful than either fire or sprays alone. Some of the new soil-applied herbicides promise better control than the phenoxy sprays when used in combination with fire.

Since fire is not a necessary step in the control program, the decision of whether or not to burn can be based on factors other than brush control, such as the desirability of opening up the area quickly, esthetics, seedbed preparation, or the consequences of fire. Some advantages of not burning prior to chemical control are the continued protection afforded by standing or fallen dead brush, retention of litter and soil organic matter, and maintaining high infiltration capacity of the soil. Some disadvantages of not burning the brush prior to chemical control include the unpleasing appearance of dead brush, and a high fire hazard until dead leaves are dropped. Also, grass is usually more easily established when the seeds are sown directly into the ashes after burning. Improved seeding techniques may be needed for establishing grass on areas of dead brush.

HOW CONVERSION AFFECTS WATERSHED RESOURCES

Treatments Applied and Vegetation Response

As part of the Arizona Watershed Program, several experimental watersheds were instrumented on National Forest lands to evaluate the effects of chaparral conversion. Treatments have been made in dense chaparral (greater than 60% crown cover, Three Bar),

medium dense (40 to 60%, Whitespar), and open or low density (less than 40%, Natural Drainages).

Three Bar Watersheds

These four watersheds (see fig. 4) are west of Lake Roosevelt in the Three Bar Wildlife Area, maintained cattle-free for game management studies. Elevation is 3,300 ft at the B weir where precipitation averages about 21 inches. Precipitation increases to about 28 inches at the top of watershed D at 5,200 ft where chaparral species intermingle with species of the oak-woodland and pine types. Parent material is coarse granite, exposure is northerly, and the upper slopes are steep, often exceeding 60 percent. Dominant shrubs are shrub live oak, birchleaf mountainmahogany, sugar sumac, and Emory oak.

Stream and rain gages were installed in 1956. Streams were intermittent, flowing about one-third of the time during the first 3 years, and yielding less than 1 inch per year average flow. In June 1959, the Boulder wildfire swept over all four watersheds, topkilling all shrubs. Shrub crown cover, which averaged 60 to 75 percent when the watersheds were established, was reduced to near zero by the fire (fig. 10). Where not subsequently treated, the brush has since

Figure 10. — Three Bar experimental watersheds before and after wildfire in June 1959. The second photo was taken 3 months after the fire, the third at the end of 3 growing seasons, the fourth after 8 years, and the fifth after 15 years.

recovered to about 90 percent of its prefire crown cover (fig. 11), although the biomass has not yet reached this level. Little herbaceous cover is present where brush is dense. Grass is present in the more open stands such as south slopes, but is sparse elsewhere.

After the wildfire, all watersheds except C were seeded with weeping and Lehmann lovegrasses *(Eragrostis curvula* and *E. lehmanniana)* and yellow sweetclover *(Melilotus officinalis)* in July 1959, but the catch was very poor. Watershed B was seeded again and C for the first time in May 1960 with weeping, Lehmann, and Boer lovegrasses *(E. chloromelas).* The resulting fair but spotty catch has gradually increased in density where shrubs have been controlled.

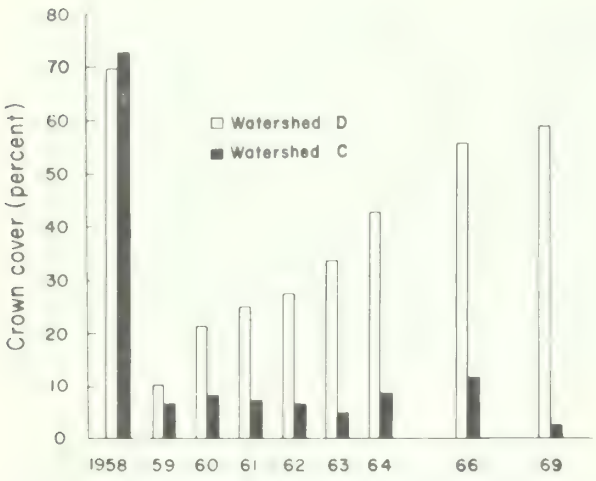


Figure 11. — Shrub cover on Three Bar C and D before and after the 1959 wildfire. Shrub recovery on C was suppressed with herbicides. Cover measurements were made at the end of the growing season of the calendar year indicated.

After the fire, watershed D (80.5 acres) was allowed to recover naturally as the control, and watersheds B (46.5 acres), C (95.3 acres), and F (68.4 acres) were subjected to various chemical treatments (table 2).

Although wildfire was not intended to be part of the original study, plans were realined to accommodate the burning as part of the treatment on watershed C. Thus, treatment on C is properly described as wildfire followed by conversion to grass using chemicals to suppress the shrubs.

The four annual aerial spray treatments on watershed C suppressed shrub regrowth, but actually killed only 42 percent of shrub live oak and 72 percent of birchleaf mountainmahogany plants. Hand treatment of surviving shrubs in 1964 and again in 1968 resulted in much better control. By 1969 shrub crown cover had been reduced to less than 3 percent. Figure 11 shows the degree of control on watershed C and shrub recovery on watershed D. Grasses and forbs on C averaged 1,200 lb/acre/year from 1963 to 1968

Table 2.--Chemical treatments and dates applied following a June 1959 wildfire on the Three-Bar watersheds B, C, and F (watershed D was used as a control, and not chemically treated)

Treatment method	Chemical	Rate of application	Watershed and year treated		
			B	C	F
		lb./acre			
Helicopter spray entire watershed	2,4,5-T	1.6		1960	
		1.6		1961	
		1.6		1962	
		1.6		1963	
Hand applied to surviving shrubs	Pelleted fenuron	3.6		1964	
Hand applied to individual shrubs on 40% of watershed:					
16.4 acres	Pelleted fenuron	18.3	1965		
2.1 acres	Granular picloram	9.3	1965		
Hand applied to surviving shrubs					
18 acres	Pelleted fenuron	6.1	1968		
70 acres	Pelleted fenuron	5.4		1968	
22 acres	Granulated karbutylate	4.4		1968	
Helicopter application, entire watershed	Granular karbutylate	20			1969
Hand applied to individual shrubs on remaining 60% of watershed	Pelleted karbutylate	6.7	1972		

(fig. 12). Ground cover is good to excellent over most of watershed C (fig. 13), and surface infiltration rates have remained high. The channel area in particular is well vegetated by weeping lovegrass. Cover is poorest on the upper, steep north exposures where lovegrasses have not done well. Forbs and half-shrubs provide fair ground cover on these sites, which account for perhaps 10 percent of the catchment. Livestock has not grazed Three Bar since 1947.

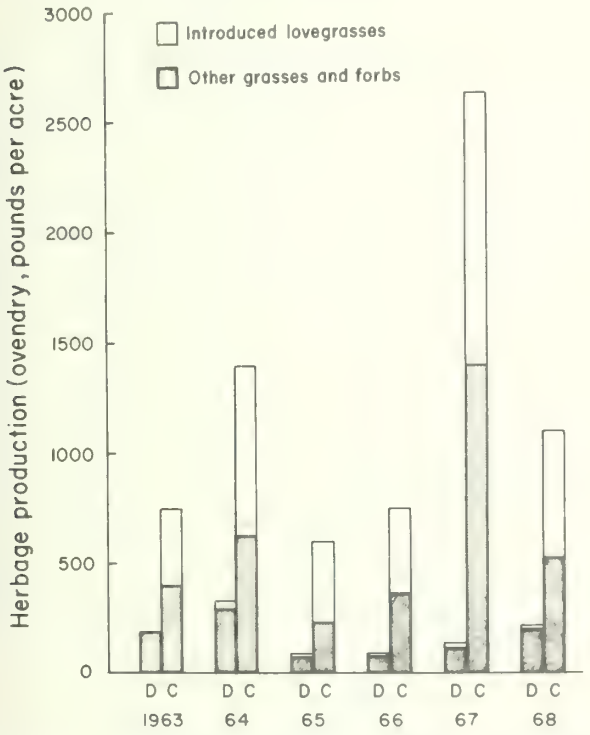


Figure 12. — Herbage production on Three Bar watersheds D and C for calendar years 1963 through 1968.

Figure 13. — Scattered shrubs persist in Three Bar C (to right of ridgeline), but ground is well covered by introduced grasses and forbs.

Watershed C was control burned in March 1971. A similar study on the use of fire for maintaining grass dominance after conversion had been made 2 years earlier on a nearby plot with good results (Pase 1971). Topkill of shrub live oak and birchleaf mountainmahogany, the two most numerous shrubs remaining on watershed C, was 71 and 68 percent. Grass was stimulated to higher production than without burning. There was no evidence of surface runoff or erosion as a result of the burn.

Shrubs on northeast-facing slopes comprising 40 percent of watershed B (see fig. 4) were hand treated in 1965 after 6 years recovery following the wildfire. Surviving shrubs were again treated in 1968. Browse plants of highest wildlife value were not treated; these species made up only about 5 percent of the total shrub cover, and included hollyleaf buckthorn, desert ceanothus, and false-mesquite (*Calliandra eriophylla).* The two treatments reduced shrub cover to about 8 percent. In spaces between shrubs, damage was light to forbs and grasses, which responded to release from shrub competition. Grass and forb production has averaged 690 lb/acre/year on the treated area, but only 300 on the untreated slopes.

The remaining 60 percent of watershed B (untreated portion, fig. 4) was treated in January 1972 in the same manner as the 1965 treatment, except that the chemical applied was karbutylate formulated as 50 percent active ingredient tablets spaced a foot or so apart on the ground surface around each shrub. After two growing seasons the treatment appears successful, although evaluation is incomplete.

Watershed F was treated in February 1969 with a broadcast application of granular karbutylate to the soil. Shrub crown cover was reduced from 55 to 4 percent in the first year. The shrubs began showing visual effects of the chemical by late April. Injury symptoms progressed rapidly during the spring months, and by early June most of the shrubs were either dead or dying. Total shrub kill increased to more than 95 percent after 2 years. Virtually all grasses and herbaceous plants also were killed by the treatments.

Phytotoxic residues remained active in the top 6 inches of soil over most of the catchment for the first 2 years, preventing growth of new plants. The only exception was along the lower channel where flow surfaced and became perennial after the treatment. A variety of forbs and grasses dominated by horseweed *(Erigeron canadensis)* invaded the channel area, where the plants rooted in the bed of the stream or in the moist banks. This band of vigorously growing plants was only a few feet wide, and ended abruptly where water was not within a few inches of the soil surface. None of the plants

showed any effects of chemical poisoning as on the rest of the watershed.

During the third growing season (1971) forbs and grasses began to appear on interior ridges in the lower part of the watershed, but many of these showed injury symptoms before fall. Invasion by forbs and grasses during the fourth growing season finally produced fair cover over all but the upper 10 to 15 percent of the watershed.

For more detailed information on treatments at Three Bar, see: Glendening et al. 1961, Pase and Ingebo 1965, Pase 1967, Pase et al. 1967, Davis and Pase 1969, Ingebo 1969, Smith et al. 1969, Hibbert 1971, McCulloch, 1972, and Davis and Ingebo 1973.

Whitespar Watersheds

The Whitespar watersheds are located about 7 miles southwest of Prescott in the headwaters of the Hassayampa drainage. The parent soil material is fine-grained granite, elevation is 5,800 to 7,000 ft, precipitation is 23 to 25 inches, and the exposure is southeast. Watershed A (303 acres) is slightly higher than B (246 acres), receives slightly more precipitation, and yields slightly more water (1.8 to 1.3 inches). Streamflow tends to be somewhat more flashy on Whitespar than on Three Bar, suggesting less storage capacity in the regolith. Gaging began in 1958.

The chaparral on the Whitespar watersheds is considered medium dense, averaging 51 percent crown cover on watershed B. Shrub live oak and true mountainmahogany are abundant. Scattered alligator junipers *(Juniperus deppeana)* to 4 ft in stem diameter are found mostly along drainageways and lower slopes. At this elevation (5,800-6,700 ft), patches of Gambel oak *(Quercus gambelii)* are common on cool northerly slopes. Cover in the channel bottoms is largely an extension of shrub types found on adjacent slopes. Herbaceous plants are sparse; annual production is less than 50

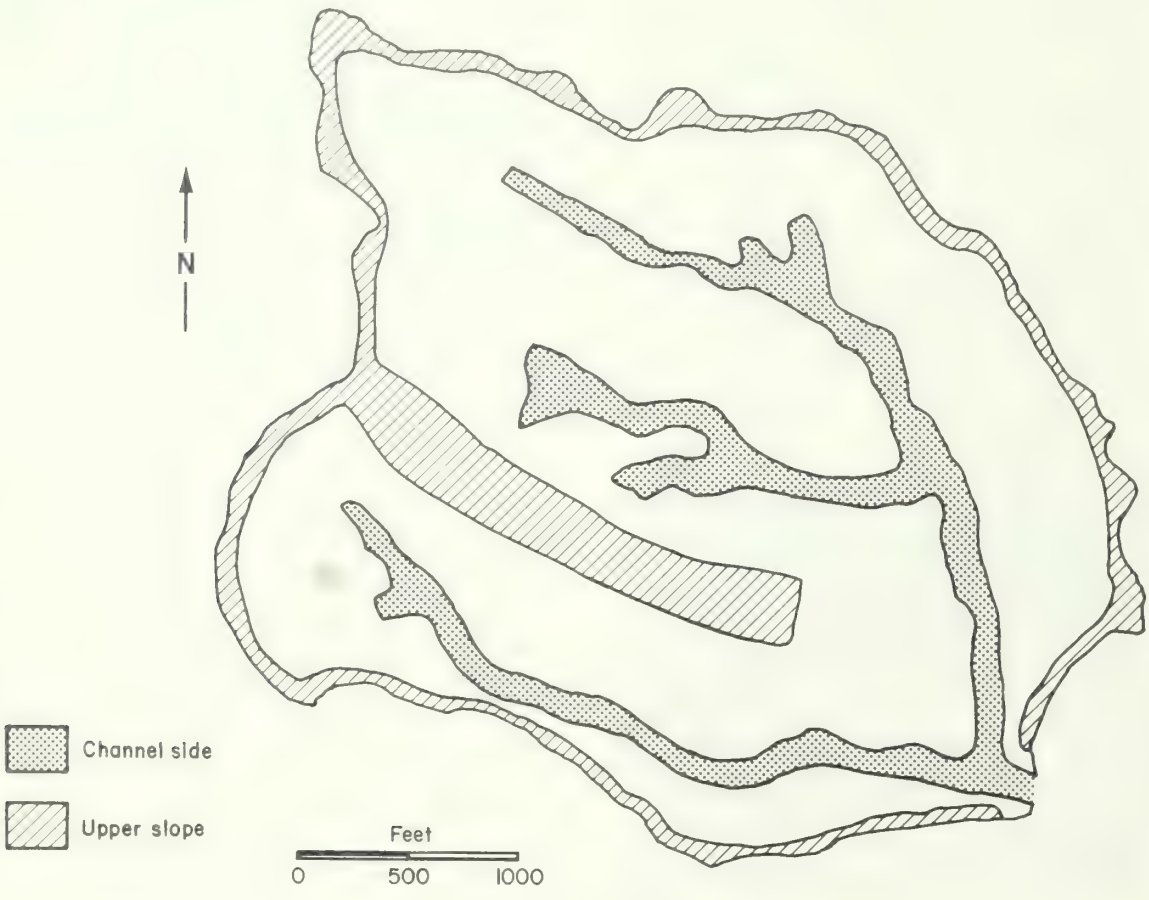


Figure 14. — Whitespar watershed B on Prescott National Forest about 7 miles southwest of Prescott. The channel-side treatment was made in 1967, the upper slope treatment in 1973.

lb/acre, about equally divided between grasses and forbs.

Conversion of channel-side brush cover to grass on B (fig. 14) was the first of a series of treatments to eventually convert the entire watershed. The second treatment was made in 1973 to convert an area of similar acreage on the upper slopes in a strip surrounding the watershed just inside the boundary to simulate a fuel break. The third and fourth treatments will convert the remaining area by southerly and northerly aspects separately.

The intent of the first treatment was to eliminate all shrubs and juniper trees that use water from the moist channel environment. By eliminating these plants, water concentrating downslope along the stream channel would be subject to less transpiration loss before contributing to the stream. Bounds of the treated zone were set at 30 ft vertical but no more than 75 ft horizontal distance from the channel. Cover in the zone was not typically "riparian;" no sycamore, alder, cottonwood, or other species often found along streams were present.

The treatment covered 38 acres, 15 percent of the watershed. Pelleted fenuron (25 percent active ingredient) was placed by hand underneath shrubs and small junipers in March 1967. Intershrub spaces were not treated to avoid killing grasses and forbs. The average rate of application on the 38 acres was 23.2 pounds (a i) per acre. Larger junipers were either cut or girdled. The single application of fenuron gave 80 to 90 percent control of the shrubs; retreatment has not been necessary. The native grasses and forbs have increased substantially on the treated area, providing generally good cover except in the patches of Gambel oak where establishment of grasses and forbs has been slow. Cattle graze both watersheds, although B was fenced after treatment to control grazing.

During the second and particularly the third summers after treatment, flannel mullein (*Verbascum thapsus*) flourished along the moist channel bottoms (fig. 15). By the fifth growing season these plants were no longer numerous. What effect this rank growth might have had on water yield is not certain. Since flow increased throughout these years, however, it is apparent that the vigorously growing weeds did not consume as much water as the brush.

For more complete details of treatments and treatment response, see Ingebo 1971, Hibbert and Ingebo 1971, and Ingebo 1972.

Natural Drainages

The four Natural Drainage watersheds (fig. 16) are designated A (13.4 acres), B (19.5 acres), C (12.1 acres), and D (9.1 acres). The original vegetation type on the watersheds was marginal chaparral, which became quite sparse and open on the more southerly exposures and on the fine-textured quartzite soils on the lower slopes. The upper slopes are diabase soils, which cover 42, 54, 44, and 28 percent of the four watersheds, respectively. Before treatment, crown cover of shrubs was 20 to 25 percent compared with covers twice to three times this dense on Whitespar and Three Bar. Shrub live oak was most abundant.

Livestock first appeared in the general area about 1880, but grazing was brought under strict control in 1934 when gaging began. The drainages were first used to study the effect of grazing on runoff and erosion. These studies

Figure 15. — Flannel mullein in the channel-side treatment area on Whitespar B third summer after the shrubs were killed.

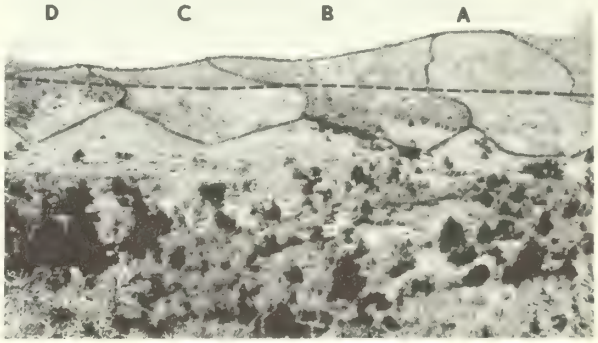


Figure 16. — Natural Drainage watersheds in 1960, 5 years after treatment on watersheds A and C. Dashed line shows contact between diabase parent material above and quartzite below.

were completed in 1952, when it was found that the intensities of grazing used in the studies had no significant effect on total water yield and sediment trapped in the weir ponds (Rich and Reynolds 1963).

Starting in 1954, the chaparral cover was eradicated to study the influence of conversion on streamflow. The basal 6 inches of each shrub on watersheds A and C was sprayed with a 6.6 percent solution 2,4-D and 2,4,5-T in diesel oil until the outer bark was saturated. Half-shrubs were not sprayed. Surviving shrubs were resprayed as necessary. Drainages B and D were left untreated as controls. By 1959, grass cover on the treated quartzite soils was about three times greater than before treatment. No significant change was noted on the diabase soils. Forbs and half-shrubs increased on all treated sites, with the greatest gain on diabase soils. The study was completed in 1971.

Changes in Streamflow

Streamflow Prolonged by Treatment

One of the more remarkable effects of brush conversion is that summer flows are prolonged well into or through dry periods. At Three Bar, the once-intermittent streams now flow yearlong on all three treated catchments. Watershed C, which was dry two-thirds of the time prior to the wildfire, has flowed continuously since. Flow in control watershed D was also prolonged after the wildfire, although it again became intermittent as brush regrew.

Three Bar B yielded no water before the wildfire. It flowed continuously after the fire for about 18 months, then was intermittent until 40 percent of the catchment was treated in 1965. Flow has been continuous since. Watershed F responded similarly, although here flow reacted more quickly to treatment. The chemical was broadcast in February 1969, and shrubs began showing injury symptoms in late April. Beginning in May, streamflow held above the expected flow rate based on the control catchment. By mid-May, flow on F was twice the expected rate, and by the end of June the difference was even larger.

This rapid response on F is important to water management interests. Streamflow responded within 3 months after chemical application, and within a few weeks of the first observed injury symptoms on the shrubs. Apparently, chemical suppression of plant activity reduced transpiration which allowed streamflow to increase. Since rainfall in this period was not enough to materially affect yield, the extra flow presumably came from stored moisture in the regolith that would have been returned to the atmosphere had the shrubs remained fully active.

Similar behavior in streamflow was noted by Crouse (1961) on the San Dimas Experimental Forest in southern California after wildfire burned a partially treated chaparral watershed (Bell No. 2). Chemical suppression of shrubs prior to the fire on 40 acres of the 100-acre catchment had materially increased yield and had created perennial flow in the normally intermittent stream. The fire in July 1960 burned all remaining vegetation. Two months after the fire, flow was 280 percent of that expected had the area not burned.

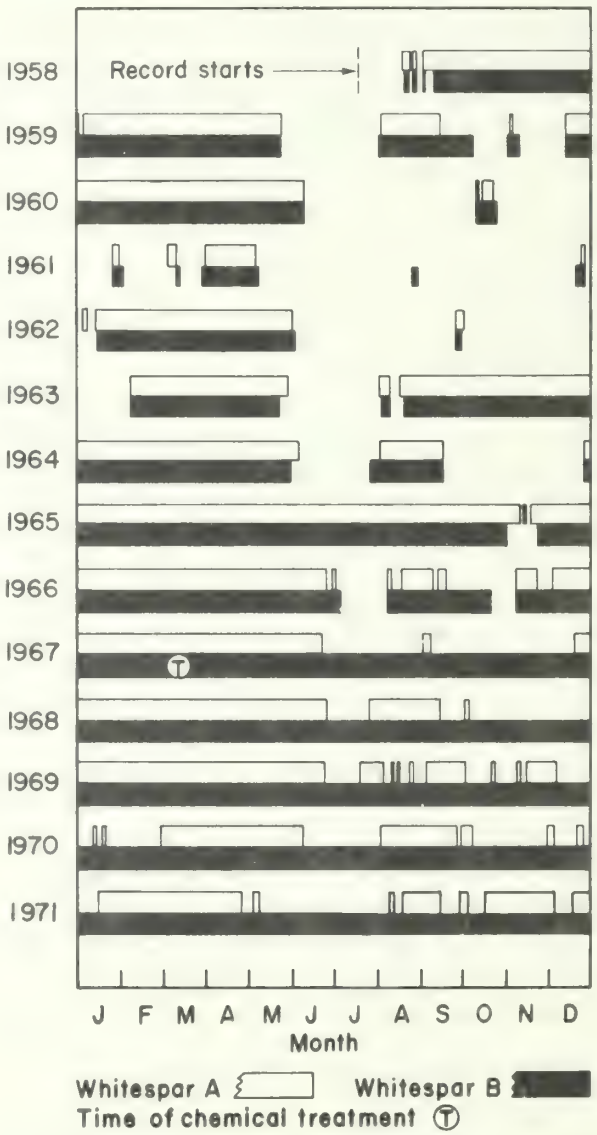


Figure 17. — Flow duration on Whitespar watersheds before and after the channel-side treatment on B in March 1967.

Flow in Whitespar B likewise became continuous after treatment of 38 acres of channel-side brush in 1967. While these lingering dry-season flows are too small to be of practical significance downstream (several years would be required to yield an acre-ft of water at the lower flow rates), they are important sources of water for wildlife and livestock. Pools persisted at intervals along the channels of B long after watershed A had dried completely (fig. 17).

Treatment did not create perennial flow in the Natural Drainages, although it is possible that duration of flows was prolonged.

Water Yield Increases

Without exception, water yield on each watershed increased after treatment. The increases were largest on Three Bar and smallest on Natural Drainages. Some of these results have been published: Three Bar B and C (Pase and Ingebo 1965, Hibbert 1971); Whitespar B (Ingebo 1971, 1972); and Natural Drainages (Ingebo and Hibbert, in preparation). Table 3 summarizes all experimental results through July 1972.

After the wildfire at Three Bar, an obvious sharp increase in overland flow was noted from the first summer rains, which were much heavier than usual that year. Although accurate measurement of stormflows in the first 2 postfire years was hampered by overtopping and sedimentation of the stream gages, it was apparent that both storm and nonstorm flows were materially increased by burning. The effects of the burning on water yield largely disappeared within 3 years on watersheds allowed to regrow to brush, although some increase persisted for several years.

We conclude from these results that water yield responds to burning as it does to other methods of reducing shrub cover, but the gains quickly diminish as the brush recovers. On watershed D, crown cover at the end of the third year was one-third of its prefire density (see fig. 11), apparently enough to effectively nullify earlier gains.

Unlike the control, watershed C continued to yield water at a rate more than four times that expected without treatment. In 11 posttreatment years (omitting the first 2 years after fire), measured yield on C averaged 7.55 inches, an increase of 328 percent or 5.78 inches more than the expected yield (1.76 inches).

Water yield on Three Bar B under 40 percent conversion since 1965 averaged 320 percent or 1.28 inches greater than expected. Prorating the increase would indicate 3.20 inches more from the 40 percent of the watershed actually treated. While it is reasonable to prorate the increase to the area actually treated, it is not correct to assume that the remainder of the watershed would respond to treatment at the same level, since the first treatment was on the more moist sites.

Water yield on Three Bar F increased 703 percent or 2.67 inches during 3 years after chemical treatment in 1969, even though these 3 years were drier than average. We expect larger volume increases from wetter years, although the percentage increase may actually decline.

On Whitespar B, the channel-side conversion on 38 acres (15 percent of the watershed) increased yield by 66 percent or 0.53 inch. These results are comparable to Three Bar experience when prorated to the area actually treated. Here, obviously, the most favorable sites were treated. We expect a lower level of response from future treatments on the upper slopes.

Table 3.--Summary of average increases in water yield for the years following treatment on each watershed

Watershed	Watershed area	Portion treated	Treatment period	Mean precipitation	Mean annual increase and 90 percent confidence interval	
	Acres	*Percent*	*Years*	*Inches*	*Percent*	*Inches*
THREE BAR:						
C	95.28	100	[1]11	23.91	328 ± 96	5.78 ± 1.69
B	46.52	40	7	20.60	320 ± 50	1.28 ± .20 [2](3.20)
F	68.39	100	3	[3]22.66	703 ± 440	2.67 ± 1.67
WHITESPAR:						
B	246.4,	15	5	20.42	66 ± 16	.53 ± .13 [2](3.53)
NATURAL DRAINAGES:						
A	13.41	100	17	17.78	23 ± 25	.25 ± .27
C	12.14	100	17	17.78	35 ± 10	.52 ± .15
A + C COMBINED	25.55	100	17	17.78	28 ± 14	.37 ± .18

[1]First 2 years after wildfire omitted.
[2]Amount prorated to portion of watershed actually treated.
[3]All 3 years drier than average.

Combined, the two treated Natural Drainage catchments averaged a 28 percent increase, or about one-third inch of extra water per year. Unfortunately, the Natural Drainages are representative of only a small portion of the chaparral in Arizona because of the shallow quartzite soils on the lower portions of the catchments. These soils are sparsely covered by brush, and probably contribute little, if any, extra water when treated. It is possible that most of the increase in yield comes from the upper portions of the catchment where the deeply weathered diabase is more typical of chaparral soils.

Two graphs based on the relationship between water yield and precipitation are presented for predicting yearly and average response to chaparral conversion. Reliability depends on how well the experimental sites represent the chaparral in general. The input data are dominated by Three Bar, particularly watershed C, in the high-response range, and by Natural Drainages in the low range. Very likely, conditions are near optimum at Three Bar for increasing yield and near minimum at Natural Drainages.

The first graph is derived by regressing yearly increases (difference between measured and predicted yields on all experimental watersheds) on yearly precipitation. Giving equal weight to all of the data, leads to an average treatment response curve (fig. 18). This relationship indicates how the onsite yearly increases vary over the range in annual precipitation so far experienced on the experimental watersheds.

The wide variation of the observed increases suggests the difficulty of precisely predicting individual annual response to treatment. The amount and seasonal distribution of rain interact with cover, soil, and site factors peculiar to each area to produce the observed responses. The tendency for wet years to produce a disproportionate amount of water has practical significance in management of these watersheds. In exceptionally wet years when natural yield exceeds storage capacity of downstream reservoirs, extra water produced by treatment does not have the same value as in dry years when the amount of the increase is much less and is needed more. Annual precipitation in the chaparral does not follow a normal distribution. Years with below-average precipitation occur almost twice as frequently as years above average, although the wet years yield more. In a year one-third wetter than average, the expected yield increase will be about eight times greater than in a year one-third drier than average. As extremes in wet and dry years are approached, the difference becomes much larger. In a year 50 percent wetter than average, the expected increase is 31 times greater than in a year 50 percent drier than average. In 37 years (1935-71) at Natural Drainages, for example, 1 year fell in each of these latter categories.

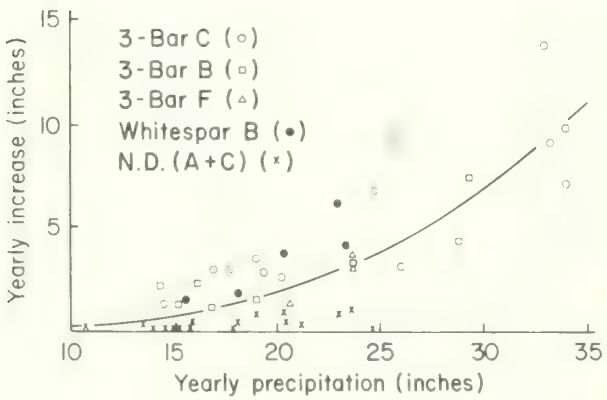


Figure 18. — Yearly increases (difference between measured and predicted yield) plotted against yearly precipitation for all treatment years on all watersheds. Three Bar B and Whitespar B data are prorated to area actually treated.

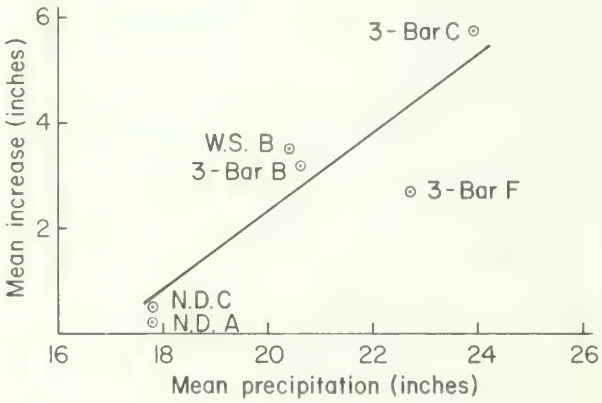


Figure 19. — Mean annual increase in water yield as function of mean precipitation. Three Bar B and Whitespar B data are prorated to area actually treated.

We therefore developed a graph (fig. 19), which is more useful for planning purposes because it estimates the mean or "normal" response to treatment expected over a period of several years. Reliable estimates of mean precipitation can be obtained for chaparral areas in Arizona from the isohyetal map of Normal Annual Precipitation prepared by the U.S. Weather Bureau and published jointly by the Arizona Agricultural Experiment Station and the University of Arizona Institute of Atmospheric Physics.

The regression is given by

$$\overline{\Delta R}=0.74\ \overline{P}-12.53$$

where $\overline{\Delta R}$ is mean annual increase in runoff and $\overline{P}$ is mean annual precipitation. Assuming 22 inches of precipitation, an approximate mean for chaparral in Arizona, the estimated $\overline{\Delta R}$ is 3.8 ±2.5 inches (90 percent confidence interval).

Some discounting may be necessary when extrapolating these onsite research results to larger areas where treatment may not be as complete or as continuous as on the experimental areas. On the small experimental watersheds, treatment was continuous on the slopes to the channels. If vegetation is left along the channel or between the channel and treated areas upslope, onsite yield increases will be smaller. The loss to downstream riparian vegetation is discussed in the next section on seasonal distribution.

To assure as much uniformity as possible between treatments, the original prescriptions called for reduction in shrub cover to less than 10 percent on the areas receiving treatment (vertical crown projection of surviving shrubs after conversion should not be more than 10 percent of the ground surface). This is not the same as reducing the shrub cover by 90 percent, unless the mature stand was 100 percent to begin with. If, for example, the original stand was 60 percent, a reduction to 10 percent would eliminate 83 percent of the shrub crown cover. Furthermore, a given level of reduction in crown cover does not necessarily mean that plant numbers are reduced by the same proportion. For example, many shrubs that are not killed outright by herbicides have crowns that are much reduced in size and function. In most of the treatments, the cover eventually was reduced to considerably less than 10 percent. Even where posttreatment cover was 8 percent on Three Bar B, many of the surviving shrubs were not healthy, and their transpiration potential was reduced.

The degree of shrub reduction is vitally important to success in improving water yield. Removing 50 percent of the shrubs in a thinning operation may give little or no increase, because each remaining plant will use more water. As thinning progresses, the rate of water use by individual surviving shrubs will approach a maximum (Campbell and Pase 1972) as physiological factors of the plant become more important in limiting transpiration than moisture supply. The effect of this relationship on water yield is hypothesized in figure 20, in which onsite increase is depicted as a curvilinear function of percent shrub removal. While the shape of the curve is highly descriptive, it illustrates the importance of removing most of the shrubs if substantial increases in yield are to be achieved.

Complete removal of shrubs on a conversion site (the portion actually treated) may not be practicable or desirable for various reasons such as cost, esthetics, or wildlife. However, it must be recognized that if water is the major objective, the conversion effort may be largely wasted unless more than three-fourths of the shrubs are eliminated. Water yield on the Three Bar control watershed, for example, was nearly back to normal 3 years after the wildfire, when shrub regrowth had reached only about one-third prefire crown cover.

Seasonal Distribution of Increased Yields

While the opportunity for increasing onsite water yield appears good, there is concern that the extra water may be lost to vegetation along stream courses draining the converted areas. Streams originating in the chaparral frequently flow through miles of semidesert before reaching rivers or storage reservoirs. These streams typically have narrow, incised channels on or near bedrock bordered by narrow bands of riparian vegetation. As the streams emerge onto lower, flatter terrain, broad meandering channels develop on flood plains of coarse alluvial outwash. During the hot summer months, transpiration by riparian vegetation is high as long as water is readily available to these plants. The streams usually flow each winter, but flow drops off in the spring, often ceasing during summer and fall except for occasional flash flows from summer storms. Appreciable streamflow usually does not recur

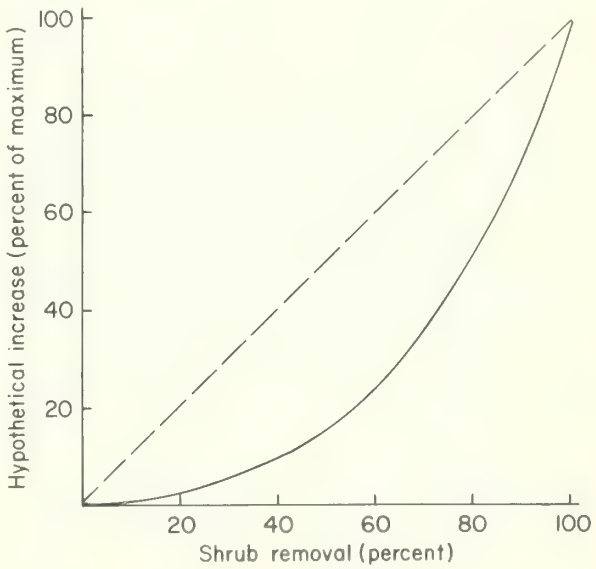


Figure 20. — Hypothetical water yield increase as function of shrub removal.

until winter rains recharge the drainage system. Subsurface flow may continue in the alluvium long after surface flow stops; in many of the channels subsurface flow is perennial.

Chaparral yields water largely in the winter and spring. About 85 percent of the water yield from the untreated experimental catchments is concentrated in the 6 winter months, November through April (see fig. 6). Sycamore Creek above the Fort McDowell gage drains 119,000 acres, about half of which is chaparral where most of the water is produced. Winter flows in Sycamore Creek make up 90 percent of the total yield (Thomsen and Schumann 1968). Other streams, such as the Hassayampa and Agua Fria north of Phoenix, yield two-thirds or more of their water in winter.

This predominately winter distribution of water yield is the key factor in realizing benefits downstream from cover conversion in the headwaters. If the yield increases also are concentrated in the dormant season, we can expect most of the extra water to be "carried through" on flow already present. Adding more water should not appreciably increase the evapotranspiration loss. Only when input is less than demand, as in dry winters or during the summer and fall, do we expect appreciable loss of the extra input.

After treatment we find that the proportion of water yield in the dormant period is much the same as before treatment, but the amount is greatly increased (fig. 21).

In most watersheds where chaparral conversion is feasible, we estimate that 80 percent or more of the increase in water yield will pass through the drainage system to storage or points of use. To arrive at this figure we assumed that very little of the winter flow increase (78 percent) would be lost, but that a substantial part of the summer increase (22 percent) might be taken up by downstream vegetation. At the present time, this estimate cannot be substantiated by measurements in the field, nor can we claim that the foregoing generalization applies to all areas.

In some types of drainage systems, a smaller proportion of the flow increase may be saved. In a low-yielding watershed, for example, where winter runoff does not normally recharge the alluvial aquifers each year, an increase in flow must first satisfy deficits along the stream course before yield can increase significantly. With water more readily available for a longer time to phreatophytes along the stream course, water use would increase at the expense of the extra water produced by treatment. It follows that, in very dry years when yield increases are small, little or no water may reach the outlet. For the most part, however, available evidence indicates that most of the extra water will get through in spite of riparian vegetation. Obviously, removal of riparian vegetation in combination with chaparral conversion would increase yields most.

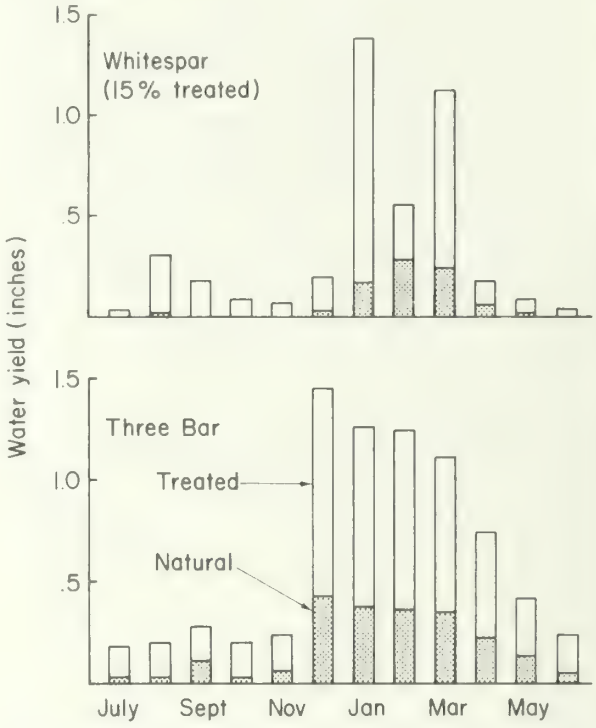


Figure 21. — Mean monthly water yield in inches on Three Bar C and Whitespar B. The upper portions of the bars denote treatment effect, which is in addition to yield that would occur without treatment. Whitespar data are prorated to channel-side area actually treated.

Erosion Following Fire and Conversion

Effects of conversion on erosion and sediment production are not readily predictable. Sediment production has been monitored on the experimental watersheds, but information is incomplete on processes causing erosion and sediment movement within the catchments and downstream.

Wettability

The extent to which infiltration is restricted because of nonwettable properties in chaparral soils under natural, burned, and treated conditions is not well known. It is common knowledge, however, that wildfire creates a very unstable soil condition, after which water runs off the surface much more readily than before. Slope erosion and scouring of headwater channels are greatly accelerated, and flooding

and sedimentation of downstream channels are expected. It is easy to demonstrate water repellency by clearing away the ash from a burned soil and placing drops of water on the mineral surface (fig. 22). The time required for the drops to infiltrate provides an index of wettability. But how does this relate to the runoff and erosion problem? Does the nonwettable layer persist long under the impact of rainfall? Which is the most important in causing overland flow and erosion, wettability or the loss of protective cover and organic matter?

Figure 22. — Drops of water fail to infiltrate mineral soil after wildfire that was hot enough to melt the beer bottle.

Scholl (1971) has demonstrated how wettability varies under an undisturbed Utah juniper stand at Beaver Creek. Resistance to wetting in the surface soil increased from completely wettable in openings between trees to highly nonwettable in the litter under the juniper canopy. It is noteworthy that one of the most intensely rilled areas found on the Whitespar watersheds after an exceptionally intense July storm was under the canopy of large spreading alligator juniper trees.

Findings in southern California by Forest Service and University scientists complement our studies on wettability of different aged stands of chaparral at Three Bar. Additional information should be gained on how wettability varies with local soils, species composition, and treatment or land-use practices such as grazing. With the present emphasis on grass conversion, it seems likely that numbers of cattle will be increased to match the increase in forage. Information is not complete on how cattle grazing may affect areas converted to grass. The effect of increased compaction and dislodgment on these steep, unstable soils, regardless of cover condition, warrants further study.

Sediment Yield

Because these soils are coarse, much of the sediment moved by the small headwater streams may be classed as bedload. If suspended by turbulent flow, the coarser particles quickly settle when velocity slows. Fine silts and clays which stay in suspension longer account for only a small percentage of total sediment. Bedload and some of the suspended sediments are trapped and measured in the weir ponding basins or sometimes in specially constructed sediment basins below the stream gages. Suspended sediment is sampled by one-shot samplers, by splitting devices, or by infrequent grab samples.

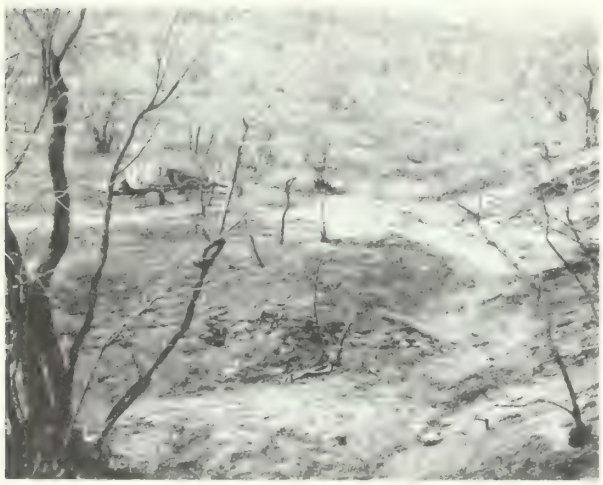
Soil moves off the slopes either by dry creep (fig. 23) and mechanical dislodgment, or by overland flow of water (fig. 24). Sometimes

Figure 23. — Soil creeping down an unstable slope on Three Bar watershed F, 4 years after treatment.

Figure 24. — Overland flow on this 2-month-old burned area carried considerable soil off the slope.

overland flows generate sufficient momentum on the slopes to start rilling, but then dissipate before reaching the channel, or if sufficient to reach the channel where the slope is less they dissipate there. By these processes, the headwater channel system accumulates sediment (fig. 25) until heavy flows flush it on downstream. Further downstream where channel gradients flatten, velocity of flow decreases and the coarse sediments are left to form broad alluvial fills.

Alternate cutting and filling occurs along the channel system as discharge rate and sediment supply fluctuate (fig. 26). The prime mover is the big storm; because these storms are rare, however, the long-term average or "normal" rate



A

B

Figure 25. — A, A small headwater channel just after wildfire, and B, the same channel 2 months later after summer rains filled the channel with sediment from nearby slopes.

Figure 26. — Alluvial deposits in channel on Three Bar watershed F cut by 8-inch storm in September 1970.

of erosion is difficult to determine. Short-term records of sediments trapped at some point in the watershed can be misleading. Sediment yield data collected in conjunction with our watershed experiments (table 4) must be evaluated with this limitation in mind.

Sediment produced during the first 3 years after the wildfire at Three Bar contrasts sharply with production in the years before and after this period, and with the other watersheds where no fire occurred. Some of the accelerated production came from the channels where sediments had accumulated, perhaps for years. However, much of it came directly off the slopes as evidenced by severe rilling in portions of the catchments. The total yield for the first 3 postfire years on Three Bar watersheds D, C, and B combined was 1,083 ft^3/acre, or 25 times the 43 ft^3/acre measured during the other 13 years (3 prefire and 10 postfire). The occurrence of much greater than average precipitation in the first postfire year, including several intense summer storms, no doubt contributed to the high sediment production. However, equally wet periods and even more intense storms were recorded during the other 13 years, including the September 5, 1970 storm. Of significance here is the fact that the area was particularly vulnerable to erosion from heavy rainfall for only a few years after the fire. This conclusion applies to treated and untreated areas alike.

When dealing with long-term erosion rates, the rare climatic event must be considered. However, it is difficult to assess the impact of a 100- or 500-year storm, especially if it should come just after a burn. The storm of September 5, 1970 was classed as a 100-year or greater storm over much of central Arizona (Thorud and Ffolliott 1973). We do not know if it reached this magnitude at Three Bar, where rainfall was 8 to

Table 4.--Sediment, in ft^3/acre/year trapped in ponding basins at or just below stream gages on experimental watersheds (suspended sediment not included except that which settled in larger basins)

Water year ending in June of year shown	THREE BAR				WHITESPAR		MINGUS			NATURAL DRAINAGE		STRIP BURN	
	D[1]	C	B	F	A[1]	B	C[1]	A	B	B+D[1]	A+C	D[1]	A+B+C
										[2]3.8	[2]2.6		
1955										4.6	2.7		
1956										[3]T	.7		
1957	0	1.1	0							.9	.6		
1958	0	0	0							1.2	.7		
1959	0	0	0		0	0	[4]21	[4]0	[4]3.7	.7	.1		
1960	933	406	1238		0	.6	4.2	0	0	.2	T		
1961	102	64	321		0	0	0	0	0	T	T		
1962	274	64	259		0	0	16	0	13	0	0	0	0
1963	.6	.3	0		0	0	0	0	0	0	0	0	0
1964	.1	.3	49	1.4	.3	T	0	0	0	8.4	.9	0	35
1965	12	1.6	34	24	.4	1.0	0	2.9	5.5	.8	T	0	0
1966	6.8	24	18	14	T	1.0	0	2.1	4.8	9.3	.2	0	45
1967	.1	.2	2.0	T	T	.6	0	0	0	2.4	.4	0	18
1968	T	2.0	6.2	T	0	.2	0	1.9	8.7	0	T		
1969	.1	T	.3	0	0	.3	.2	0	0	0	0		
1970	.1	.1	.2	.2	0	0	0	0	0	.6	0		
1971	T	.1	.3	[5]59	0	0	.4	0	0	1.0	.2		
1972	0	.2	.3	34	0	0	0	0	0				
Mean	83	35	121	15	T	.3	3.0	.5	2.6	1.8	.4	0	16

[1]Control watershed.
[2]Mean annual sediment yield for period 1936-54.
[3]T = Trace = less than 0.1 ft^3/acre/year.
[4]Part of July 1958 not included; unknown amount of sediment occurred.
[5]Short by unknown amount that overflowed basin during storm of September 5, 1970.

10 inches. The most impressive thing about the storm at Three Bar was the lack of erosion. Despite heavy flows, the only watershed to produce sediment at the gaging site was the most recently treated watershed F, where more than 60 ft^3/acre came from the channel and slopes. The lack of sediment from the other catchments is attributed to lack of overland flow and stable channel conditions, particularly in the lower portions of the catchments.

The treatment on Three Bar F has shown that chemical control of vegetation can lead to substantial erosion on steep, unstable slopes. No erosion was detected on the catchment until 18 months after the treatment, which killed virtually all plant cover. Starting with the big storm in September 1970 (water year 1971 in table 4), sediment production remained heavy during most of the moderate to heavy rains through 1972. Sediment production was heaviest during October 1972 (not in table 4) when rainfall exceeded 14 inches on the watershed. At least 20,000 ft^3 (300 ft^3/acre) came out of watershed F. More than half of this came from the channel, as indicated by channel cross sections. The remainder came primarily from the steep upper slopes comprising about 10 percent of the watershed where vegetation has not recovered.

Control burning in contour strips can also produce sediment, although exposing only a portion of the slope each year to fire reduces the impact of broadcast burning. Three small catchments on the Sierra Ancha Experimental Forest were treated with prescribed fire in early fall for 4 consecutive years beginning in 1961. One-fourth of each catchment was burned each year in either 50-, 100-, or 200-foot-wide strips. A fourth catchment was left undisturbed as a control. The objective was to test prescribed burning in strips to temporarily reduce chaparral cover for improving water, forage, and browse production (Pase and Lindenmuth 1971).

Sediment moved off the treated slopes on three occasions during the treatment and evaluation period (table 4), twice during periods of heavy summer rains, and once during the wet months of November and December 1965 when

rain and snow totaled 17.2 inches. No erosion or overland flow was observed on the control catchment.

Sediment yield did not vary consistently with strip width, probably because of differences in slope, which appeared to be more influential in causing overland flow and rilling on the burned areas. Residual litter and relatively low burning temperatures were important factors in controlling sediment yield. Erosion was less noticeable on lightly burned areas where 70 percent or more of the litter residue was retained than on areas where less than 60 percent was retained.

Mass Slippage after Conversion

Mass soil slippage is not common in Arizona chaparral in contrast to certain portions of southern California where this form of soil erosion occurs after heavy storms and is accelerated by burning brush or converting to grass (Rice et al. 1969, Rice and Foggin 1971). Two probable reasons for less mass slippage in Arizona are slope steepness and rainfall. While generally thought of as being steep, most chaparral in Arizona is on gentler terrain than the problem areas in California, where most slips occur on slopes greater than 80 percent. Rainfall also is lighter in Arizona; both the size and frequency of storms are less.

A small soil slip did occur, however, on treated watershed C at Three Bar during the wet winter of 1972-73 after prolonged rainfall. The soil mass was 24 ft wide, 80 ft long, and about 3 ft deep. It moved enmass about 75 ft down a short, 65 percent slope near the upper ridgeline of the watershed. Wildfire in 1959 followed by grass seeding and chemical control of shrubs had converted the slope cover to mostly forbs and grasses.

The question of importance here is whether or not treatment was the primary cause of the slippage. If the event was largely the result of an atypically unstable soil mass being saturated to the point of slippage by prolonged, heavy rains, then the phenomenon will recur only rarely, and it need not be of particular concern. On the other hand, if treatment of the shrubs was the major cause of the soil mass becoming unstable under the abnormally wet conditions, then mass slippage may become a distinct hazard associated with treatments on steep slopes.

Summary of Erosion Effects

In summarizing treatment experience to date, it seems probable that most management practices will increase erosion for a time following chaparral conversion. The increase is likely to be greatest from broadcast burning, and least from mechanical or chemical eradication of shrubs if replacement cover is established soon after treatment. The experimental evidence at Three Bar shows that conversion to grass after wildfire does not reduce erosion any more than allowing brush to recover. Sediment production on Three Bar watersheds C and B over the past 10 years did not differ significantly from the brush-covered control. Since cattle have not grazed Three Bar, these cover conditions should be near optimum.

Over the long run, however, conversion should reduce erosion because the wildfire cycle will be interrupted and the heavy postfire erosion reduced or eliminated (Boster and Davis 1972). Safe grazing and other land-use practices must be strictly followed, however, to assure that the replacement cover will protect the soil at least as well as brush.

Chemical Contamination and Nutrient Changes in Stream Water

Chemical Contamination

The suitability of herbicides depends on many factors in addition to their effectiveness in controlling brush: toxicity to wildlife, livestock, and humans; persistence in soil; susceptibility to leaching; and effects on grasses, irrigated crops, and the products of streams, lakes, and reservoirs. The relative importance of these factors varies with the chemical. The problem is further complicated by factors such as location; size of area treated; the frequency, rate, type, and season of application; soil properties; topography; and precipitation. In some cases it may be necessary to regulate the size of treatments closely to avoid the buildup of residues in water supplies.

Picloram content of stream water from Three Bar B (46 acres) was monitored after a spot-treatment application in early February of 19.5 pounds (ae) of picloram in pellet form to 2.1 acres in a small side drainage (Davis and Ingebo 1973). Rain shortly after the treatment flushed some of the chemical through the soil and into the main stream channel. Concentrations of 350-370 p/b (parts per billion) were measured during the first 3 months after periods of heavy rainfall. Concentrations were much lower than this most of the time. Picloram was no longer detectable after 14 months and 40 inches of accumulated

rainfall. Considerably higher contamination levels would be expected if picloram were applied over the entire watershed. Since the side drainage represented only 4.5 percent of the watershed, there was a possible 22-fold dilution of the chemical. An estimated 4.5 percent of the picloram applied was lost to stream water.

On the basis of present toxicological data, this treatment would not represent a hazard to humans, wildlife, or aquatic organisms. Although direct use of water from the treated watershed when picloram levels are 46-370 p/b could damage sensitive crops such as cotton, dilution with water from untreated areas would reduce picloram to harmless levels.

A spot treatment of fenuron on 18 acres of Three Bar B (40 percent of the watershed) resulted in very low stream water contamination for 18 months. Fenuron pellets were applied by hand in January to individual bushes and clumps of bushes at 20 pounds (ai) per acre. The overall application rate on the treated slopes was 6.1 pounds per acre. For the first 6 months, concentrations fluctuated from zero to 7 p/b. During the following winter, fenuron concentrations reached 11 p/b after several heavy rainstorms. After 18½ months and 31 inches of precipitation, fenuron was no longer detected.

It is estimated that only 0.11 pound, or 0.1 percent of the 112.5 pounds of applied fenuron left the watershed in the stream water. Because fenuron has a very low toxicity rating, the type of treatment applied has an extremely low contamination potential.

Fenuron was monitored on Whitespar B after spot treatment of 23 pounds (ai) per acre on 38 acres of mixed chaparral along the major stream channels. Shrubs were treated 75 ft either side of the channel. The highest concentration detected in the stream water was 420 p/b, 33 days after treatment following heavy rains. Subsequent concentrations ranged from 50 to 280 p/b during the first year, and from 8 to 40 p/b during the second year. Cumulative rainfall was 27 inches the first year and 50 inches for both years. Trace amounts of fenuron or its breakdown products were still present in the stream water 27 months after treatment, but not after 3 years.

An estimated 21.3 pounds, or 2.4 percent, of the 884 pounds of applied fenuron left the watershed via streamflow. Although trace amounts persisted for a long time, the relatively small loss of fenuron from a treatment area adjacent to the stream channel again indicates that fenuron has a low contamination potential.

Granular karbutylate was broadcast by helicopter in mid-February to Three Bar F (68 acres) at the rate of 20 pounds (ai) per acre. This application gave nearly total brush kill. In the future, lower rates might be found to give adequate brush control, but for this study the high rate was used to insure brush eradication. The study will provide data on extent and duration of stream water contamination caused by a maximum application rate.

Weekly water samples were analyzed throughout the first year; more frequent samples were analyzed during the first month and during periods of heavy rainfall. Method sensitivity for karbutylate in water was 10 p/b. Water samples taken at the V-notch weir immediately after the application was completed contained 22 p/b karbutylate, presumably from granules falling on a short stretch of surface streamflow immediately above the weir. During the first year the concentration of karbutylate never exceeded 51 p/b. Concentrations ranging from 11 to 51 p/b were present in 15 out of 59 samples. Fourteen of the fifteen samples containing detectable residues occurred within 4 months of the treatment. Rainfall during the first year totaled 17.8 inches.

Such low levels of contamination during the first posttreatment year are very encouraging, but a complete assessment of the contamination potential of karbutylate treatments requires further research.

Nutrient Changes

Nutrients released from decomposing chaparral litter are normally recycled into the living vegetation. When the plants are killed, however, the nutrients can be lost via leaching, runoff, and erosion. This phenomenon would be expected to continue until the area is revegetated and perhaps even afterwards, depending upon the replacement vegetation. Such loss of nutrients would deplete soil fertility and contribute to excessive enrichment of streams and lakes.

The maximum effect that a chemical conversion of chaparral on a granitic soil might be expected to have is being determined at Three Bar watershed F. Nearly all chaparral vegetation on this 68-acre watershed, including grasses and forbs, was either killed or topkilled by a broadcast soil application of karbutylate.

Composition of stream water changed surprisingly little following treatment. During the first posttreatment year, only nitrate ion was substantially increased in the stream water. The normal nitrate concentration in stream water from the untreated control watershed, about 0.2 p/m, was independent of precipitation and streamflow. In contrast, nitrate concentrations in stream water from the deadened watershed were highly dependent on precipitation and

streamflow. Nitrate increased to 24 p/m following a 2.1-inch rainstorm, and to 36 p/m following a 3.3-inch storm. Nitrate concentrations gradually declined to normal levels over a period of several weeks.

During the second posttreatment year, an intense 8-inch storm during the 1970 Labor Day weekend provided an opportunity to document what may possibly be the near-maximum effect of a single storm event on nutrient losses from a deadened chaparral watershed. It is remarkable that nitrate was the only ion affected by the heavy rainfall. It increased from a normal value of 0.2 p/m up to 56 p/m (a 280-fold increase), then gradually declined to 1 p/m in December. Nitrate increased to 20 p/m following a 3-day storm in December that yielded 2.2 inches of rain, then gradually declined, but did not return to normal until May. The nitrate concentration in stream water from the control watershed remained at a normal level of about 0.2 p/m throughout the year.

Properties of the stream water from the deadened watershed which were unaffected by the Labor Day storm were total soluble salts, electrical conductivity, pH, and the following ions: calcium, potassium, magnesium, sodium, chloride, sulfate, carbonate, ammonium, and phosphate. Bicarbonate concentration decreased slightly in the stream water from both control and deadened watersheds.

Although streamflow from the treated watershed has remained well above normal, nitrate concentrations have increased only after moderately heavy rainfalls. During prolonged dry periods, when the nitrate concentrations from the deadened and control watersheds were the same, loss of nitrate nitrogen from the deadened watershed was proportionately greater than that from the control watershed, however, due to the increased volume of streamflow.

We anticipate that nitrate will continue to be leached from the watershed in abnormal amounts until the organic nitrogen compounds are exhausted, or until vegetation is reestablished and a new steady state of nitrate loss is reached. Recent findings from older partial watershed conversions indicate that high levels of nitrate still persist 8 years after treatment, even though the areas were revegetated with grass and forbs.

Additional studies are needed on other soil types and with other types of watershed manipulations. Conversions need to be designed that will minimize nitrate enrichment of stream water. Studies on the effects of brush eradication on soil fertility, and determinations of nutrient budgets for natural and treated chaparral ecosystems are also needed for proper assessment of chaparral manipulations.

Effects of Brush Control on Wildlife and Livestock

Since most chaparral shrubs are not relished by domestic livestock, the carrying capacity of mature chaparral is relatively low. Annual carrying capacity ranges up to 10 animal units per section, depending on slope, accessibility, and vegetal composition. Stands with significant amounts of true mountainmahogany, desert ceanothus, hollyleaf buckthorn, and Wright silktassel may have somewhat higher stocking rates. Sprouts of shrub live oak, as well as the more palatable shrubs, provide fair forage after a fire. Forage value decreases as the shrubs mature. Shrubs also provide emergency forage during drought and occasional years of heavy snowfall (Pond et al. 1968).

Conversion invariably increases the forage production and carrying capacity for livestock. On the Tonto Springs beef study, Prescott National Forest, annual livestock weight gains averaged only 9.4 lb/acre/year on native chaparral, while animals grazing adjacent pastures converted to weeping lovegrass gained 81.4 lb/acre (USDA Forest Service 1969).

Both mule deer and white-tailed deer are common in chaparral areas. Populations vary locally from 4 or 5 to as many as 20 or 30 per mile^2 (Swank 1958), with an overall average in 1955 of perhaps 10/mile^2 (Hanson and McCulloch 1955). Populations tend to be high where shrub species composition is favorable, and low where shrub live oak and skunkbush form almost pure stands (Swank 1958). McCulloch (1973) found that mature chaparral was an important diet constituent for white-tailed deer on the Three Bar wildlife area. Mature browse represented up to 50 percent of the diet during late fall, winter, and early spring. In addition, the mast, fruits, and berries of mature browse constituted as much as 65 to 70 percent of the midsummer diet.

As with cattle, shrub sprouts provide better forage for deer than do mature or decadent shrubs. Therefore, providing suitable areas of sprout regrowth can have a beneficial effect on deer (Reynolds and Sampson 1943, Swank 1958, Reynolds 1967).

Studies conducted on the Three Bar watersheds by the Arizona Game and Fish Department (McCulloch 1972) showed that brush control on watershed C reduced two major white-tailed deer foods while it increased a third. All shrub fruits, important during summer, were eliminated and most palatable browse species such as hollyleaf buckthorn were killed. Herbaceous forbs increased greatly, particularly the summer-growing species, many of which bear some green basal foliage through winter. Although this food was probably the main reason for deer using watershed C more than the

adjacent untreated brush (Pase et al. 1967), forbs cannot totally substitute for the mast and browse removed by treatment, since deer never eat forbs exclusively, even in seasons of greatest forb abundance. Untreated cover must be retained nearby if the quality of deer habitat is to be maintained. Since no part of watershed C (95 acres) is more than 300 yards from a boundary, the deer using this watershed can easily reach and use adjacent untreated chaparral.

More specific data are needed as to the time of day and season of year during which deer use the treated watersheds. To this end white-tailed deer are being equipped with bells and radio collars and tracked by the Arizona Game and Fish Department.

Observations made on two belled white-tailed does in 1971-72 (McMichael 1972) indicate that during daylight hours the deer prefer undisturbed brush to treated chaparral for both feeding and bedding. These findings are at variance with the earlier observations based on pellet-group counts taken during the postfire period 1959 to 1968, which showed substantially more deer use on the treated sites. Either the deer use the treated areas much more at night (when observations were not made) than during the day, or some other explanation is necessary to account for the apparent discrepancy. More information of this type is needed to help clarify the ultimate value of the various herbicide-treated areas as deer habitat.

Deer-use patterns in chaparral near Prescott differ from those at Three Bar. Mule deer are dominant in this area. Chemical control on 38 acres of streamside shrubs and junipers at Whitespar watershed B has not affected deer use significantly. The data indicate, however, that deer use is concentrated on upper slopes and ridgetops. The next treatment phase will be imposed on these upper areas, and could affect deer more directly.

Rootplowing and seeding lovegrass at Tonto Springs near Prescott effectively converted chaparral to grassland. Deer use as indexed by pellet-group counts on 80-acre treatments was significantly and consistently lower on conversions by a ratio 1:3 (Urness 1974). However, forbs and grasses associated with the dominant lovegrass provided high-quality forage largely unavailable in mature chaparral stands.

Loe and White (1972) surveyed bird and small mammal populations on this and other rootplowed areas. Numbers of species were similar on treated and intact stands, but total numbers observed were higher on conversions.

In reviewing the significance of forage quality in wildlife management, Hanson and Smith (1970) suggest several reasons why habitat is improved by brush treatments. Opening up dense brush provides space for animal movement as well as an increase in the abundance and nutritive quality of new browse and forage. Also, the variety of food is increased as forbs become more abundant and shrubs sprout. The beneficial boundary or "edge" effect resulting from treatments is also known to improve wildlife habitats in general.

Large chaparral conversions can adversely affect wildlife. Repeated herbicide applications may tend to create monocultures, although fears of creating "biological deserts" are unwarranted. Conversion practices that intensively convert large areas to grass should be avoided (McCulloch 1972). Treatments should be small and irregular, with as many shrubs and forbs left within the treated areas as practicable to provide a variety of food. Probably no more than half the total areas should be converted (Reynolds 1972), but precise prescriptions have not been determined. The nonconverted areas need not be ignored. Periodic burning or some other form of treatment might materially improve them for wildlife.

SUMMARY AND CONCLUSIONS

Chaparral covers 3 to 4 million acres in Arizona. While land managers rate chaparral low in commercial value, it yields about 0.1 acre-ft of water per acre per year, and produces some forage and browse for game and livestock. It also provides food and cover for a variety of wildlife, and to many it is esthetically pleasing as a natural ground cover. Access is limited because of the dense brush, however, and protection against fire is difficult and costly. For many years the chaparral has remained under protective management only; no cultural practices have been applied to any significant degree to improve its natural productive capacity.

A continuing demand for agricultural water combined with a declining water yield from central Arizona watersheds during the 1940's and early 1950's provided the impetus for studies to increase the water supply from forest lands, including chaparral. Several experimental watersheds were established, the chaparral was treated, and effects of treatment on streamflow, erosion, wildlife, and grazing values were evaluated.

Streamflow has been substantially increased by eradicating deep-rooted shrubs and replacing them with shallow-rooted grasses and forbs that use less water. The amount of increase varies considerably between sites because of complex interactions between precipitation, soil, aspect, local climate, and other factors that

affect the disposition of water by the indigenous shrub cover. The method and amount of shrub reduction also affect treatment response.

Posttreatment increases in average annual streamflow on the experimental watersheds varied from one-third inch to over 5 inches. Estimates can be made of onsite increases in water yield if conversion to grass reduces shrub cover to less than 10 percent. For example, if mean precipitation is 22 inches the expected onsite increase from figure 19 is 3.8 inches. These gains in water yield can be maintained if posttreatment use and maintenance of the grass cover are well planned, and geared to changing conditions and needs.

The tendency for large increases in wet years and for flows to be prolonged into or through dry periods have profound effects on aquatic habitat and channel environment of the normally intermittent headwater streams. Some adjustments in the channel are likely under prolonged, high flows; channel erosion may accelerate until the system conforms to the new level of activity. On the other hand, stability is added when water-loving plants such as sedges, watercress, willows, and alders invade where chaparral species once grew. Wildlife, livestock, and water-oriented recreation activities will benefit from these changes. Overall, enhancement of the stream environment is expected.

Some of the extra water will be lost to riparian vegetation along streams draining the converted areas, particularly during dry periods when streams normally do not flow. However, since nearly 80 percent of the increase is produced in the dormant season when streams are normally active, the proportion lost should be small, probably less than 20 percent.

Chaparral control methods that have proved effective in Arizona are mechanical, prescribed burning, chemicals, and chemicals in combination with the others. Rootplowing is the only mechanical method used extensively in chaparral conversion. Steep slopes and rocky soil are the limiting factors; less than 8 percent of the chaparral can be treated this way. Where it can be used, however, the rootplow offers the best method of shrub control. Shrub mortality is usually 80 percent or better, and re-treatment is seldom necessary. Grass is readily seeded in the plowed soil, usually in the same operation. Costs are moderate.

Prescribed burning modifies the density, stature, and composition of brush stands, but kills outright only a few species such as manzanita. Most shrubs sprout vigorously after fire to the detriment of grass and water savings. Therefore, if eradication is a management objective, burning must be combined with other control methods. Two uses of prescribed fire offer promise and should be researched further. Fire can be used to topkill and open up mature stands, and to prepare a seedbed for grasses. Maintaining grass after resprouting brush or brush seedlings start to gain competitive advantage over the young grass stand may be difficult. Here chemicals can be used to good advantage to maintain the balance in favor of grass until grass is established well enough to carry fire. At this stage, fire can be used repeatedly to topkill and thus control shrubs.

Herbicides, properly used, can perform an important function in eradication and control of woody plants. A variety of chemicals have been used; several are being tested for effectiveness and for contamination of soil and stream water. Chemicals may be applied to the foliage as sprays or to the soil surface in the form of granules or pellets. Of the foliage sprays, the phenoxy group (2,4-D; 2,4,5-T; silvex) and picloram, as well as phenoxy-picloram mixtures, are commonly used. The phenoxy herbicides are most economical for large-scale projects, but they do not provide adequate control of the dominant shrubs. Substantial shrub mortality cannot be expected until after several annual applications. One advantage, however, is that they are more toxic to brush than to grasses, thus favoring grass in conversion practices.

Soil treatments offer several advantages over foliar sprays for controlling brush. Application is easier and the problem of drift is eliminated. Selective treatment of individual shrubs or species is easy by hand application, although this method is not economical for large-scale treatments. Soil-applied chemicals are for the most part potent brush killers (eradication of most shrubs is possible with one application) but most are toxic to grass and other desirable plants as well. Selectivity is possible by hand application but not by broadcasting, although broadcasting large pellets 3 to 6 ft apart may kill shrubs yet allow grasses to grow between. This technique is being explored.

Herbicides which are effective as soil treatments are fenuron, picloram, karbutylate, and bromacil. None is registered for watershed use as yet, and the availability of fenuron is uncertain. Cost of these chemicals at application rates high enough to assure shrub eradication in one or two treatments may be prohibitive, although expensive treatments may be economically feasible if they need not be repeated for many years.

The herbicides discussed in this report were tested experimentally, and their use does not imply that they are recommended or registered for watershed use. The use of any herbicide for project or commercial purposes must conform with regulations of the Environmental Protection Agency and be registered for the intended use. Regulations will undoubtedly become in-

creasingly strict in order to insure adequate protection of the environment. Only when a product passes the many toxicological hurdles required is it granted registration for use as specified on the label. It is important, therefore, that label directions be read carefully and strictly followed. Latest registration information regarding herbicides can be obtained from the Agricultural Extension Service of the U.S. Department of Agriculture.

Stream water from the treated watersheds shows moderate to low contamination by chemicals applied. Only in large-scale treatments would herbicide contamination be of concern; even then, dilution with water from untreated areas would probably reduce chemical concentrations to harmless levels. Water quality can also be endangered by accelerated leaching of nutrients from treated areas when the normal nutrient cycle is interrupted by killing the vegetation. Limited studies indicate that nitrate concentration is the only water property materially affected by complete deadening of brush and herbaceous vegetation on a granitic watershed. More study is needed to determine the extent of loss, and how it affects soil fertility and enrichment of streams and lakes.

Erosion probably will increase for a time following most conversion practices. The impact is likely to be greatest from broadcast burning, and least from mechanical and chemical control of shrubs, if replacement cover is established soon after treatment. Treatment on excessively steep slopes (over 60 percent) or particularly unstable soils should be avoided. Safe conversion on slopes between 40 and 60 percent depends largely on soil and site factors which vary considerably within the chaparral. Treatment criteria should be developed on the basis of soil, anticipated use, and maintenance problems peculiar to each site. Over the long run, conversion should reduce erosion by reducing or eliminating the heavy erosion cycle set off by periodic wildfires. This reduction is based on the assumption that the replacement cover will protect the soil as well or better than brush, and that grazing and other land-use activities will be carefully planned and followed.

Conversion increases forage for livestock, and influences wildlife in several ways. On converted areas, near complete eradication of shrubs (necessary if water yield is the major objective) will eliminate the habitat of some species while providing new habitat for others. If treatment areas are kept small and interspersed with native chaparral, protective cover and browse will always be available nearby, and the edge effect created by the treated openings will enhance the overall wildlife environment.

Although much remains to be learned about chaparral in Arizona, enough information has been gained to clearly indicate that the productive capacity of these areas can be greatly enhanced. Increased water, forage, wildlife, and recreation benefits can be realized either singly or in combination by modifying the shrub cover. Results from research and pilot testing suggest that it will be possible to design chaparral conversions that will be safe, effective, and not detrimental to the environment.

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On areas favorable for treatment, conversion to grass reduces fire hazard and substantially increases water yield and forage for livestock. If treatment areas are kept small and interspersed with native chaparral, protective cover and browse for game animals will always be available nearby, and the edge effect created by the openings will enhance the overall environment for wildlife. Chaparral control methods that have proved effective in Arizona are rootplowing, prescribed burning, chemicals, and chemicals in combination with the others. Stream water from treated watersheds shows moderate to low contamination by herbicides. Over the long run, conversion should reduce erosion by reducing or eliminating the heavy erosion cycle set off by periodic wildfires in unmanaged chaparral.

Keywords: Watershed management, chaparral, brush control, water yield improvement, soil erosion, sediment yield, habitat improvement.

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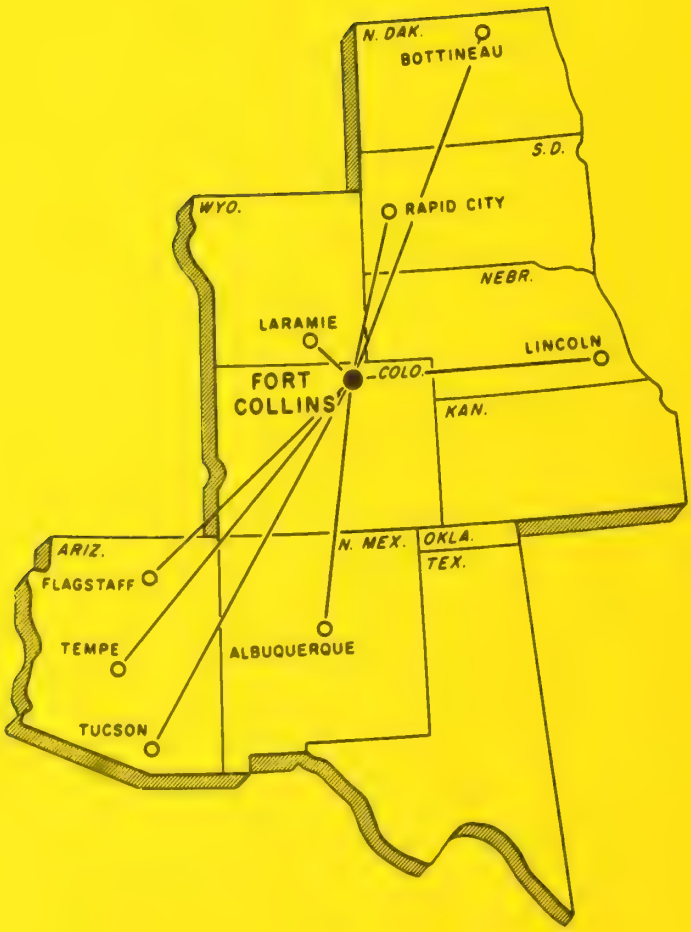
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CHAPARRAL CONVERSION POTENTIAL IN ARIZONA

Part II: An Economic Analysis

by Thomas C. Brown
Paul F. O'Connell
Alden R. Hibbert

ABSTRACT

Is chaparral conversion on National Forests in the Salt-Verde Basin economical? An inventory revealed 139 chaparral areas totaling 332,796 acres meet certain crown cover, slope, and managerial criteria for conversion. The costs of converting portions of these areas to grass and maintaining the conversion over a 50-year period were compared with the benefits to society in terms of increased water yield and forage for livestock, and reduced firefighting costs. Using fire as the main conversion tool, 96 areas have a benefit-cost ratio greater than 1; using a soil-applied herbicide, 72 areas meet that economic criterion. Proper management should favorably affect soil movement, wildlife habitat, and esthetics. Recreation use would be unaffected in most areas.

Keywords: chaparral control, multiple use, economic evaluation, cost estimation

USDA Forest Service
Research Paper RM-127

August 1974

CHAPARRAL CONVERSION POTENTIAL IN ARIZONA

Part II: An Economic Analysis

by Thomas C. Brown, Economist
Paul F. O'Connell, Principal Economist
Alden R. Hibbert, Hydrologist
Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained in Fort Collins in cooperation with Colorado State University. Brown and O'Connell are located in Tucson in cooperation with the University of Arizona; Hibbert is in Tempe in cooperation with Arizona State University.*

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CHAPARRAL CONVERSION POTENTIAL IN ARIZONA Part II: An Economic Analysis

by Thomas C. Brown, Paul F. O'Connell, and Alden R. Hibbert

INTRODUCTION

The 8.4 million acre Salt-Verde Basin includes the Salt and Verde River Watersheds of central Arizona above Granite Reef Dam (fig. 1). The Basin supplies most of the water for the Phoenix Valley, in addition to providing timber harvesting, grazing, mining, recreation, and hunting opportunities. As the human population of central Arizona increases, demand for these products also increases. The familiar question — what should the product mix be? — continually becomes more pressing.

Fifty-nine percent of the Salt-Verde Basin is managed by the U.S. Forest Service. The 850,000 acres of chaparral on National Forest lands in the Salt-Verde Basin are the subject of this study. The Forest Service position in managing these lands is set forth in the Southwestern Region's Multiple Use Management Guide:[2]

> Management emphasis in the Chaparral Zone will be directed towards increasing water yield, reducing fire hazard, and improving forage for wildlife and livestock. In the establishment of ground cover, palatable forage species for livestock and wildlife will be given preference to the extent they will not be detrimental to the watershed. Soil stabilization measures will be included in all treatment prescriptions.

The Region's *Chaparral Management Position Statement*[3] adds that "the Forest Service objective is to achieve the full potential of the chaparral type through carefully designed modification and control of the ecosystem."

Conversion of chaparral to grasses and forbs is generally considered the main means of reaching the Forest Service objective. This involves control or complete removal of dense

[2] *U.S. Dep. Agric., For. Serv. Multiple-use management guide. For. Serv. Handbook, R-3, p. 340.3. Albuquerque, N. Mex. 1967.*

[3] *U.S. Dep. Agric., For. Serv. Chaparral management position statement, Southwestern Region. Albuquerque, N. Mex. 1972.*

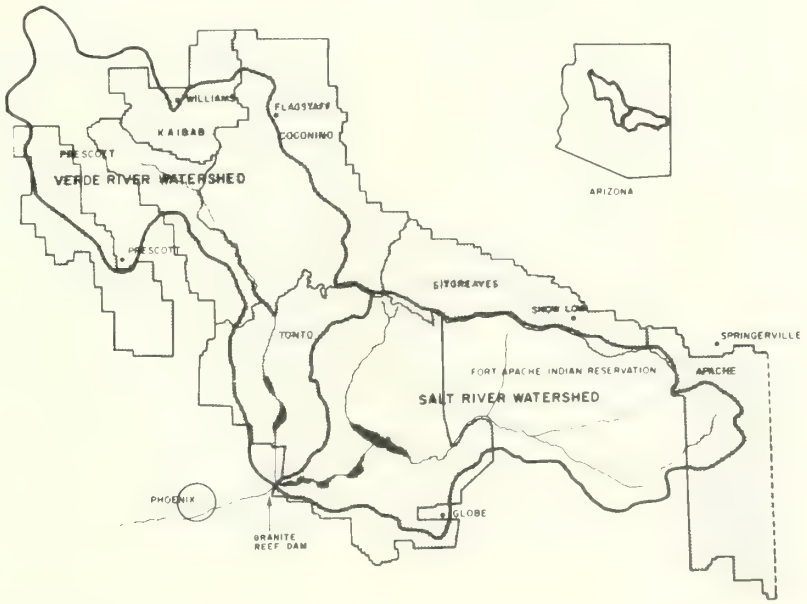

Fig. 1. — The Salt-Verde Basin includes parts of the Prescott, Kaibab, Coconino, Tonto, and Apache - Sitgreaves National Forests.

patches of chaparral, seeding the treated areas with grasses and forbs, and subsequent maintenance of the conversion for as long as benefits are desired.

Part I (Hibbert, et al 1974) of this two-part series describes the chaparral vegetation type, methods used for its modification, and the effect of such methods on water, soil, and wildlife. This part is an economic evaluation of the application of such methods on National Forest land in the Salt-Verde Basin. The study method was as follows:

1. Delineate chaparral areas meeting certain criteria for conversion.
2. Estimate costs of conversion.
3. Determine effects of conversion on yields of water, forage, and sediment, as well as impacts on fire hazard, recreation use, esthetics, and wildlife habitat.
4. Develop value criteria for quantifiable effects and impacts.
5. Integrate costs and measurable benefits into an economic framework using benefit-cost analysis.

Our primrary objective was to put the potential of chaparral conversion on National Forest lands in the Salt-Verde Basin in perspective. The conclusions drawn about the economic feasibility of conversion are based on the individual consideration of 139 separate chaparral areas within the Basin. Some details about the individual areas are found in the Appendix.

Primary costs and benefits of treatment and maintenance were estimated over a 50-year study period. Full employment of capital and labor were assumed. The two primary objectives of public investment listed by the U.S. Water Resources Council (1973) — to enhance national economic development and to enhance environmental quality — were evaluated. Adverse effects on these objectives (such as funds diverted from other uses to implement conversion) were considered *costs*; beneficial effects (such as increased forest productivity) were termed *benefits*.

To fully account for the primary benefits, all returns were identified to whomever they may accrue. Chaparral conversion increases U.S. Treasury revenue through additional grazing fees and reduced firefighting costs. Primary benefits also accrue to water users, ranchers, and recreationists. Constant 1972 dollars were assumed over the 50-year evaluation period. Inflation is assumed to have similar relative impacts on benefits and costs. The streams of benefits and costs are expressed as present value (PV), which is defined as:

$$PV = \sum_{t=1}^{50} [Y_t^- / (1+i)^t] \qquad [1]$$

where Y_t is the annual cost or benefit, i is the discount rate, and t is time in years. In this study, i is 6-7/8 percent, as presently recommended by the U.S. Water Resources Council (1973).

The "with and without" evaluation procedure (U.S. Senate 1962) was used, where "without" signifies a continuation of present management and "with" denotes the conversion alternatives evaluated here.

Alternatives to conversion for reaching the same ends are not dealt with. Alternative methods of increasing runoff and reducing fire hazard might, for example, be more efficient than conversion. Likewise, methods of financing the investment are not considered. One alternative is for the entire financial burden to be paid from tax revenues. In line with more recent thinking (U.S. Water Resources Council 1973), however, water users, ranchers and the public sector could all play a part in the financing, commensurate with the benefits which would directly accrue to each.

CHAPARRAL INVENTORY

An inventory of all National Forest chaparral in the Salt-Verde Basin delineated 139 areas that could be considered for conversion to grass. The criteria, method, and results of the inventory are described in this section.

Criteria

Because of the large study area, a detailed on-site inventory of physical characteristics and managerial considerations for all chaparral land was unrealistic. The lack of reliable, uniform secondary data limited the criteria for delineation to the following three:

1. Vegetation. The chaparral cover (vertical crown projection) must be at least 30 percent since clearing less than 30 percent cover would have minimal effects on runoff, forage and fire hazard. Furthermore, an area of chaparral which supports more than a 30 percent overstory of pinyon-juniper or ponderosa pine cover should be classified as the overstory species.
2. Slope. The slope of the delineated area should not be greater than 60 percent (31 degrees). Potential erosion hazard, uncertainty of establishing grass, cattle grazing habits, and conversion methods are the main reasons for this constraint. (The 60 percent cutoff is, of course, arbitrary. The appropriate cutoff point would actually vary from site to site depending on soil, grazing, and other conditions.)

3. Operational considerations. The proximity of a conversion area to wilderness areas, private land, recreational facilities, and travel and water influence zones must be evaluated. Chaparral in the following areas was not considered convertible: (1) within designated wilderness areas, (2) within one-quarter mile of a designated wilderness area (providing a buffer zone for the wilderness), and (3) on private land within a forest boundary. In most cases, the effect of conversion on recreation areas and influence zones can only be determined by careful on-site examination; areas that might fall into this category were included.

These criteria enabled us to delineate the maximum chaparral acreage that could be considered for conversion. A more detailed examination of these areas would also consider soils, parent material, access, wildlife habitat, fire hazard, and livestock grazing management.

Methods and Data Sources

The following three sources provided the primary information about the vegetation and its density: (1) the Pacific Southwest (PSW) — I hydrologic unit inventory covering all National Forest land in the Salt-Verde Basin[4], (2) the comprehensive Hydrologic Surveys done on approximately 50 percent of the dense chaparral on the Tonto National Forest, and (3) the vegetative type map of the Tonto National Forest.[5]

The PSW survey, completed 5 years ago by the Pacific Southwest Hydrologic Study Team of the U.S. Forest Service, was the most useful because it covered all chaparral areas and also gave some estimates of percent cover. The vegetation delineations, which were based almost exclusively on aerial photographs, proved quite accurate for most areas; the only major discrepancies were due to different definitions of chaparral.

The Comprehensive Hydrologic Surveys were completed by the Forest Service Salt-Verde Study Team. The surveys included in-depth inventories of the vegetation and soils of the following areas: (1) the Mazatzal hydrologic subprovince, including individual reports on the Sycamore Creek and East Mazatzal planning units; (2) the Cherry Creek and Salome Creek planning units and Connor Canyon and Turkey Creek-Bear Head Canyon project areas of the Sierra Ancha hydrologic subprovince; and (3) the Upper Salt River, Pinal, Pinto Creek, San Carlos, Spencer, and Sixshooter project areas of the Globe hydrologic subprovince.

A complete vegetative inventory of the Tonto National Forest was developed from aerial photos, personal observation, and aid from the district personnel. The inventory does not delineate percent vegetative cover, but was helpful in outlining the general vegetation.

The information provided by the above sources was verified at the Ranger District level. District personnel were asked to comment on all chaparral areas in an attempt to correct any inconsistencies.

Slope data were taken directly from U.S. Geological Survey topographic maps. Wilderness boundaries and access routes were taken from Forest Service maps. Information about access problems, recreation use, and other management considerations was obtained from discussions with Forest personnel.

Delineation of Chaparral

Chaparral in general. — Over 90 percent of the chaparral in Arizona lies in a wide band stretching across the central part of the State to the south and west of the ponderosa pine belt. The Salt and Verde Rivers and their tributaries drain approximately half of this chaparral. That portion of the major band of chaparral not in the Basin lies northwest of Phoenix.

Nearly all of the chaparral on the Tonto National Forest is also in the Basin. The Prescott has close to 400,000 acres of chaparral, but only about 30 percent drains into the Verde River. While the chaparral on the Coconino lies in the Basin, there are less than 30,000 acres, and only isolated small patches of more than 30 percent cover. The Kaibab National Forest, while partially in the Basin, has no chaparral. Some chaparral is found on the Apache National Forest south of where the Salt River drains the Apache.

Chaparral areas suitable for further consideration. — Of the 850,000 acres of National Forest chaparral in the basin, 82 percent is on the Tonto, 15 percent is on the Prescott, and 3 percent is on the Coconino National Forest. Some 200,000 acres in wilderness areas and 263,000 acres with less than 30 percent brush cover were eliminated from consideration. A total of 43,621 additional acres were eliminated because of slope and operational criteria. The remaining 347,967 acres are contained in 139 areas: 108 are on the Tonto (fig. 2) and 31 are on the Prescott (fig. 3). Also outlined in figure 2, but not included in the acreage totals, is previously

[4] *The maps and accompanying data are maintained at the Southwestern Regional Office, U.S. Forest Service, in Albuquerque, New Mexico.*

[5] *The hydrologic surveys and vegetative map are maintained at the Tonto National Forest Supervisor's Office, U.S. Forest Service, Phoenix, Arizona.*

converted Brushy Basin (area T40). If the 9,171 acres of private land scattered throughout the areas are subtracted , 332,796 acres of National Forest land remain (table 1).

The 139 areas range in size from 88 to 12,160 acres; the mean size is 2,440 acres. Smaller areas were outlined solely on the basis of the criteria stated. Larger areas were sometimes divided to make them easier to consider. Where possible, the division line conforms to a district boundary, watershed boundary, or allotment fence.

Seven areas on the Tonto National Forest (fig. 2), totaling 15,950 acres, are presently held under special agreements which may make intensive management infeasible; five areas (T41, 42, 47, 48, and 50) are in the Three Bar Game and Fish Agreement area in the Mazatzal Mountains, area T84 is on the Sierra Ancha

Fig.2. — Possible conversion areas on the Tonto National Forest.

Experimental Forest, and area T19 includes the Tonto Forest Seismological Observatory near Payson. Although grazing is not presently permitted on six of the areas, grazing was assumed as if the area were not under the special management.

Pattern of Conversion

Decision makers have the option of converting all or only part of a chaparral area. Although complete conversion yields maximum increases in water runoff and forage, partial conversion (leaving unconverted patches within the general area) is more favorable to wildlife, probably is more esthetically pleasing, and, in addition, leaves the steeper slopes untreated.

Table 1.--Summary of possible chaparral conversion areas, Salt-Verde Basin, Arizona

Ranger District	No. of areas	Nat'l Forest land[1]	Percentage on slopes--		Possible conversion portion[2]	
			<30%	Between 30% & 60%	Size	% of total
		Acres			*Acres*	*Percent*
Tonto						
Cave Creek	5	21,137	16	76	10,196	48
Globe	24	56,909	35	59	27,033	48
Mesa	15	37,083	10	78	22,250	60
Payson	17	44,560	47	47	23,514	53
Pleasant Val.	30	47,203	28	66	24,856	53
Roosevelt	17	28,423	14	72	16,936	60
Sub-total	108	235,315	28	64	124,786	53
Prescott						
Chino Valley	2	4,447	67	32	2,668	60
Thumb Butte	10	11,744	62	35	4,333	37
Verde	7	31,832	21	68	15,770	50
Walnut Creek	12	49,458	57	42	28,355	57
Sub-total	31	97,481	46	49	51,126	52
Total	139	332,796	33	60	175,912	53

[1]A total of 9,171 acres of private land have been subtracted.
[2]A maximum of 60 percent of the delineated areas was considered convertible; a lesser conversion rate was slated for 42 areas.

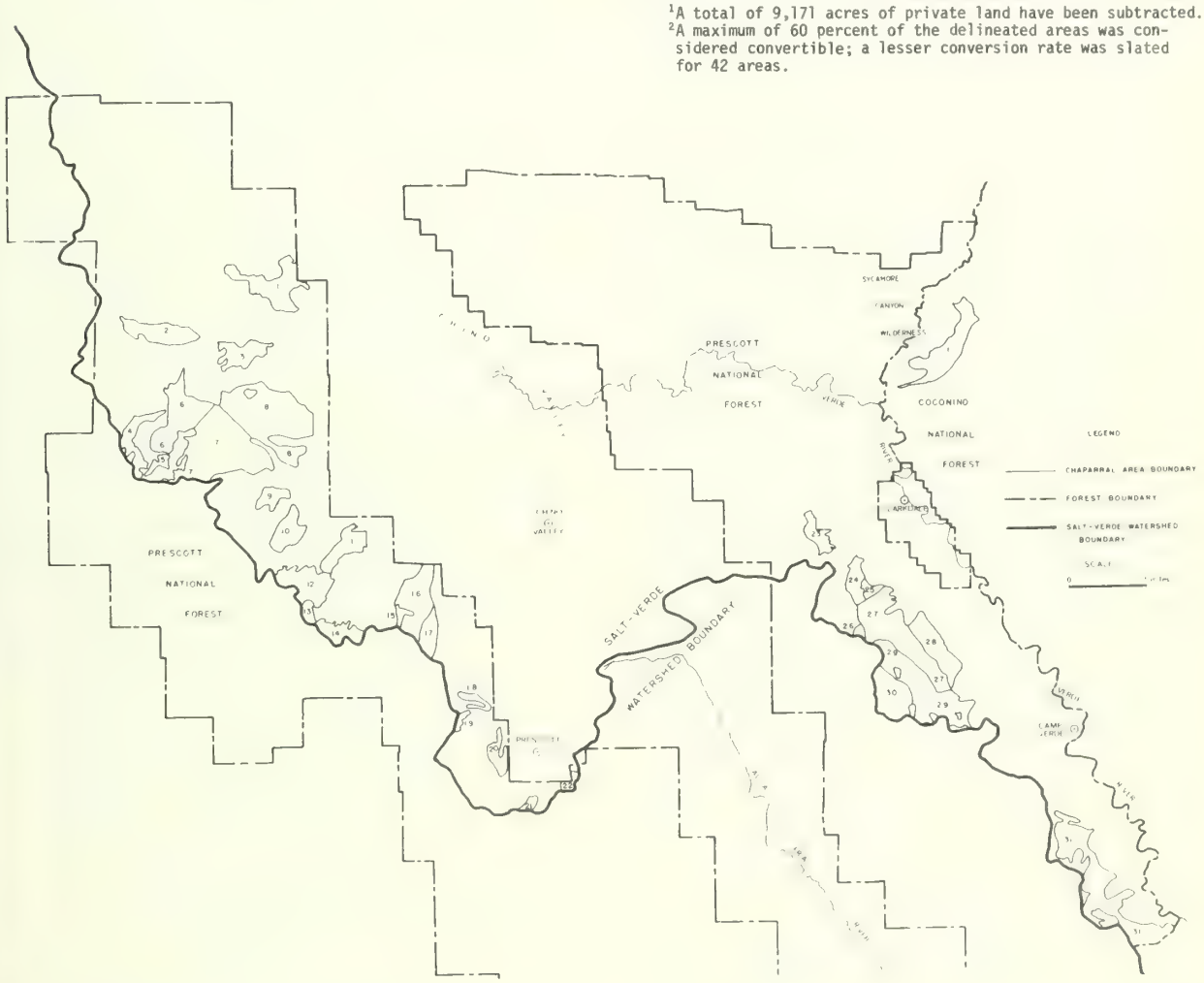

Fig. 3. — Possible conversion areas on the Prescott National Forest.

Currently the Forest Service favors partial conversion. The *Chaparral Management Position Statement* of the Southwestern Region states:

> Cultural practices, when appropriate, will be used to re-establish irregular patterns of different chaparral age classes, intermixed with forb, grass, and timber types to establish as nearly as possible a natural fire-induced ecological phenomenon. Such practices will be applied on areas culturally improved by design and also areas which have been devastated by uncontrolled wildfires.

We assumed the maximum allowable conversion of any given chaparral area to be 60 percent; thus, at least 40 percent of the area would remain as patches of chaparral within the conversion area. The 60 percent conversion maximum is a compromise between the water user and rancher on the one hand, and those concerned with wildlife and esthetics.

Because of the gross scale of the data utilized in the inventory, some of the 139 delineated areas contain small patches covered by (1) chaparral of less than 30 percent cover, (2) other vegetation types, or (3) slopes greater than 60 percent. Where any combination of these three situations exists on more than 40 percent of a delineated area, less than 60 percent of the area can be converted. Examination of each of the 139 areas, based on this qualification, resulted in a reduction of the maximum allowable conversion for 43 areas (Appendix).

The actual conversion acreage was thus reduced to 175,912 acres, or 53 percent of the total acreage of the delineated areas (table 1, the two right-hand columns). This is the maximum possible acreage which could be converted based on (1) the vegetation, slope, and operational criteria, (2) the inclusion of seven areas presently under special management, and (3) a conversion pattern which preserves portions of the original stand.

CONVERSION COSTS

Two treatment and maintenance models were evaluated. Conversion Alternative I consists of an initial burn followed by periodic maintenance burns and broadleaf herbicide applications; Alternative II consists of an initial soil-applied herbicide followed by maintenance burns.[6] Refer to Part I for descriptions of several herbicides used in brush treatment. A maximum of 60 percent of each area is to be converted with both alternatives. If more than 60 percent of an area were inadvertantly burned under Alternative I, the excess portions would be allowed to return to brush through exclusion of seeding and herbicide. For Alternative II, predetermined patterns should be easily created.

The alternative conversion models were developed to determine costs; their use here should not be considered an endorsement. While individual readers may question the timing, amounts, or actual inclusion of particular items in the conversion schemes, small changes should not significantly affect the computed present value costs.

The cost models simulate treatment and maintenance costs for all 139 areas, assuming conversion began in 1972 and is maintained for 50 years. Inputs to the cost models were derived from information collected at the Forest and

Table 2.--Unit costs of conversion[1] (1972 dollars)

Item	Cost	Unit
Personnel		
Crewman	$ 3.31	hr.
Caterpillar operator	5.19	hr.
Per diem		
Camping	10.00	day
In town	19.00	day
Equipment		
Helicopter lease (450.00 minimum)	150.00	hr.
Helicopter helper	0.25	mi.
Tractor, D-7 type		
Haul	336.00	r. trip
Lease	17.14	day
Operate	25.80	day
Pickup, 1/2-ton, 4-wheel-drive		
Lease	2.59	day
Operate	0.07	mi.
Pickup, 3/4-ton, 4-wheel-drive		
Lease	4.14	day
Operate	0.135	mi.
Carryall, 1/2-ton, 4-wheel-drive		
Lease	2.59	day
Operate	0.075	mi.
Bus, 20-passenger		
Lease	4.82	day
Operate	0.21	mi.
Pumper, slip-on ECO pump	0.50	day
Supplies		
Seed (weeping lovegrass)	1.25	lb.
Herbicide		
Broadleaf	2.02	lb. active
Soil-applied	6.00	lb. active
Burning	0.06	acre
Other		
Rootplowing	18.21	acre
Overhead		
10 percent of listed cost.		

[1]Source: U. S. General Services Administration rental rates, and communication with Forest Service personnel.

[6]*Another possible alternative consists of initial burning with biological maintenance (goat grazing for example). Because of lack of experience with biological control, this alternative was not evaluated.*

District level of the Tonto and Prescott National Forests. Table 2 lists the unit costs for the inputs in 1972 prices.

In an attempt to include all possible conversion costs and to anticipate the unexpected, three precautions were taken. (1) Use of a large — 31 man — crew was assumed for the initial burning of all areas in Alternative I. (2) A generous application of soil-applied herbicide is assumed for Alternative II. (3) A maintenance seeding of 20 percent of each area was included in case grass does not catch in certain portions of the conversion. On the other hand, we assumed there would be no costly escapes from prescribed burning.

Conversion Schedule

We assumed a maximum of 600 acres in any one area would be converted each year. In areas with more than 600 acres to be converted, conversion would proceed in annual stages of 500 acres. Area T13, for example, contains a total of 1088 acres, 60 percent (653 acres) of which is to be converted; 500 acres would be treated the first year and 153 acres the second year. If 2027 acres of area T30 were to be converted (60 percent of 3379 total acres), 500 acres would be treated in each of the first three years, with 527 acres treated the fourth year. While on-the-ground situations may suggest somewhat different annual staging procedures than used here, they should not greatly affect costs.

Conversion Alternative I. — An environmental impact statement for the proposed treatment must first be completed and reviewed. In the first year of the conversion schedule, access problems are solved, fuelbreaks and firelines are installed, and the first portion of the area to be converted (the entire area if less than 600 acres are converted) is burned and seeded. The following maintenance schedule follows initial treatment of each portion:

Year 2	- herbicide spray
Year 4	- maintenance burn and 20 percent maintenance seed
Year 5	- herbicide spray
Year 7	- maintenance burn
Year 10	- maintenance burn
Year 11	- herbicide spray
Years 13-50	- a 12-year cycle beginning in year 13 of maintenance burns the first, fifth, and ninth years and herbicide spray the tenth year.

In addition, access improvements are maintained every three years beginning in year 5. For area T13, 500 acres would follow the schedule in the years stated, while the remaining 153 acres would follow the schedule one year later.

Conversion Alternative II. — An environmental impact statement must be completed prior to conversion. In the first year of the soil-applied herbicide alternative, access problems are solved and the herbicide and seed are applied to the first portion of the area to be converted. The conversion is maintained with a burn the third year and every four years thereafter. A 20 percent maintenance seed immediately follows the first burn. A fireline is installed around the upper half of each portion to be burned at the same time as the burn. Access improvements are maintained every three years.

Cost of Conversion — Alternative I

This section describes Alternative I in detail, concluding with an example of the individual costs of a 50-year conversion scheme for a particular area. Conversion Alternative II is subsequently described, but only briefly.

Environmental impact statement. — Environmental impact statements have only recently been required for Forest Service vegetation management. Based on limited Region 3 experience, we assumed that 20 areas would be included in one statement (combining has previously been allowed) at a cost of $200 per acre. The cost of the environmental analysis, an input to the statement, is covered in overhead. The weighted (for area size) average per-acre cost of the impact statement for all 139 areas is 16 cents. The average unit costs of this and other cost categories are listed in table 3.

Access. — Vehicular access to each area was examined to determine whether improvements would be necessary to allow movement of men and equipment. We assumed that new or improved roads would remain open for public use and be periodically maintained.

Areas with access problems were sorted into two categories, (1) areas presently lacking access routes, and (2) areas served by primitive roads that need improvement (not all primitive roads need improvement). Within the first category, four classes were established reflecting the difficulty likely to be encountered in installing a road. Classes A, B, C, and D require 2, 6, 10, and 12 days, respectively, to install one mile of road. Within the second category, two classes (A and B) were established, requiring 1.3 and 3.0 days, respectively, per mile of improvement.

The crew for providing and maintaining access for all classes in both categories requires

Table 3.--Average undiscounted unit costs of converting 139 chaparral areas, Salt-Verde Basin, Arizona (1972 dollars)

Category	Cost	Unit
Environmental impact statement	$ 0.16	acre[1]
Install road		
A (2 days/mi)	971.39	mile
B (6 days/mi)	1,801.18	"
C (10 days/mi)	1,884.78	"
D (12 days/mi)	2,390.28	"
Improve primitive road		
A (1.3 days/mi)	423.04	"
B (3.0 days/mi)	696.76	"
Maintain access improvements	291.93	"
Rootplowing	18.21	acre
Mechanical preparation for burning		
Fuelbreaks (25% of perimeter)	3.38	"
Firelines (50% of perimeter)	0.57	"
Burning		
Initial (fuelbreaks, firelines, area)	10.99	"
Maintenance (per application)	0.21	"
Seeding		
Initial	3.85	"
Follow-up (20% of area)	8.75	"
Aerial herbicide application		
Broadleaf spray (per application)	3.31	"
Soil-applied	33.01	"

[1]The weighted (by area size) average per-treated-acre cost.

the following men, equipment, and supplies:[7]

2 crewmen
1 tractor, D-7 type
1 tractor operator
1 pickup (1/2 ton, 4-wheel drive)
seed for road shoulders (4 pounds per acre)

Engineer's time necessary to mark the right-of-way for the new access is included in overhead. For the Tonto National Forest, the crew comes from Payson, Pleasant Valley, or Globe, whichever is closer. The crew comes from Prescott for the Prescott National Forest. The men either return home each night or camp at the site, whichever is less expensive. Costs of hauling the caterpillar (table 2) and transporting the crew are included. Average costs per mile of providing and maintaining access, as figured for those areas where it is necessary, are listed in table 3.

Fuelbreaks and firelines. — We assumed fuelbreaks and firelines were a necessary prerequisite for burning. For areas without natural fuelbreaks, we assumed that one fourth of the perimeter would be made a fuelbreak, one half a fireline, and the remaining one fourth left as is. Where areas have adjacent boundaries or can otherwise utilize the same breaks or lines, the cost is shared. The fuelbreaks are 132 yards wide (48 acres per mile) and the firelines are one tractor-width wide. Estimates of the acres per hour which a D-7 tractor can clear in California (Green, et al 1963) were utilized to determine time requirements:

Chaparral density	Days per mile for installation	
	Fuelbreak	Fireline
Medium	10	0.8
Heavy	16	1.4

[7]*Based on communication with Joy J. Baldwin, Timber, Fire, and Watershed Staff Officer, Tonto National Forest, Phoenix, Arizona, 1972.*

The crew and its origin are the same as those for providing access. Table 3 lists average per-acre installation costs. The fuelbreaks and firelines are later burned by the burning crew.

Rootplowing.— Although burning is the major initial treatment method of Alternative 1, rootplowing is also utilized. Forest personnel delineated 5,560 acres within the 139 areas where rootplowing is feasible. The average cost of rootplowing on the Prescott National Forest from 1969 through 1971 — $18.21 per acre in 1972 prices — was applied to the 5,560 acres.

Burning.— The time necessary for burning the fuelbreaks, firelines, and initial acreage is 5 days for 400 to 600 acres, 4 days for 200 to 400 acres, and 3 days for less than 200 acres. Subsequent (interior) portions require less time because the lines and breaks are already available. The time necessary is 4 days for 400 to 600 acres, 3 days for 200 to 400 acres, and 2 days for less than 200 acres. These requirements will naturally vary with circumstances. The burning crew, which is the same for all areas and size burns, includes the following:

31 crewmen
1 pickup (1/2 ton, 4-wheel drive)
3 pickups (3/4 ton, 4-wheel drive)
3 slip-on pumpers
1 carryall
1 bus
burning supplies

Crew composition was based on the number of firefighters historically available at each district. Crews consist of men from the local district plus,if necessary, men from neighboring districts. Transportation and per diem costs were calculated for all crewmen. A followup crew of two men with a pickup and pumper remains at the scene for 2 days after each burning operation. The average per-acre cost over all 139 areas of the initial burn is $10.99 (table 3), slightly higher than the $10.00 per-acre cost estimated by Duran and Kaiser (1972, p.11) for chaparral burning.

Maintenance burns are important in controlling sprouting chaparral species and maintaining a vigorous grass stand. The maintenance burn crew consists of two men with a three-quarter ton pickup, a pumper, and burning supplies. The average cost over all areas is $0.21 per acre (table 3).

Seeding. — We assumed two pounds of weeping lovegrass, at $1.25 per pound, would be seeded per acre. Per-acre costs of combinations of grasses and forbs, such as a mixture of weeping lovegrass, Lehmann lovegrass, and yellow-blossom sweet clover, would be similar. All areas are seeded following initial burning. Anticipating that grass may not become established in some portions of the treatment area, we also assumed a 20 percent followup seeding after the first maintenance burn.

The seed is applied by helicopter (except for the rootplowed areas, which are initially seeded during the rootplowing) at a rate of 372 acres per hour. The helicopter and helper come from Phoenix for the Tonto National Forest and Marana for the Prescott National Forest. The ferry charge ($150.00 per hour at an average flying time of 50 miles per hour) and the helper's charge ($0.25 per mile) are assumed to be split between three areas. In addition, a three-man seeding crew (1) transports the seed from the Forest headquarters to the area in a three-quarter ton, 4-wheel drive pickup, (2) loads the seed, and (3) calibrates the seeder. The average per-acre cost of seeding the 139 areas is $3.85 for initial seeding and $8.75 for followup seeding (table 3).

Herbicide application. — Broadleaf herbicides are used in the second year to control sprouting chaparral species and provide a more favorable environment for establishment of a grass stand, and periodically during the remainder of the study period as maintenance. The spray is applied at a rate of 10 gallons per acre (a 10 percent active mixture) and costs $2.00 per acre. Helicopter and crew costs are similar to the seeding costs except for the addition of a slip-on pumper to the pickup. The average per-acre cost of broadleaf herbicide application over all areas is $3.31 (table 3).

Overhead. — The normal overhead used by the Forest Service is at least 30 percent, but much of this would be incurred whether or not areas are converted. The additional planning and supervision costs which would be incurred *with* conversion are assumed to be 10 percent of conversion costs.

Complete costs of converting one area — an example. — Area T13 (fig.2) is located about 10 miles north of Payson on the Payson Ranger District of the Tonto National Forest. The majority of the chaparral ranges from 40 to 60 percent cover, which is considered "medium." Sixty percent of T13 (653 acres) will hypothetically be converted. Except for small isolated exceptions, the slopes are less than 60 percent. There is sufficient access to the area. The perimeter of T13 is 7.8 miles, one-fourth (1.94 mi.) of which will be a fuelbreak and one-half (3.9 mi.) of which will be a fireline. Nearly 23 working days will be necessary to install the fuelbreaks and firelines: (1.95 mi.) (10 days/mi.) +(3.9 mi.) (0.8 day/mi.) = 22.62 days.A permanent tractor

crew maintained in Payson will install fuelbreaks and firelines, and will return to Payson each night. The burning crew consists of 10 men from Payson, 6 from Pleasant Valley, and 15 from Globe. The 10 men from Payson will return there each night, but the other 21 men will camp at the site due to the distance from their homes and the travel time involved. After the burning operations, two men will remain for two more days with a pickup and pumper to watch for fires. After the areas are burned and seeded, they are maintained with periodic herbicide sprays and burns. Table 4 lists the individual costs of the complete conversion and maintenance of T13 over 50 years.

Cost of Conversion — Alternative II

Environmental impact statement and access costs are identical to those for Alternative I. Soil-applied herbicide at a rate of 5 pounds active material per acre has shown promise of eliminating chaparral growth on experimental plots. Assuming a 5 pound rate, at a cost of $6.00 per pound of active ingredients, the herbicide will cost $30.00 per acre. Because the herbicide is in solid form rather than liquid, the aerial application costs are similar to those for seeding in Alternative I. The total average cost of the herbicide application is estimated to be $33.01 per acre (table 3). The first maintenance burn,

Table 4.--Complete costs for Alternative I conversion of area T13 (1972 dollars, undiscounted)

Item	Cost
I. Environmental impact statement	$200.00
II. Access	0.00
III. Fuelbreaks and firelines (23 days)	
2-man crew ($26.48/day/man)	1,218.08
Cat operator ($48.99/day)	1,126.77
Cat hauling	336.00
Cat lease ($17.14/day)	394.22
Cat variable ($25.80/day)	593.40
Half-ton pickup lease ($2.59/day)	59.57
Transportation (20.4 mi. round trip)($0.07/mi)	32.84
Overhead (10%)	376.09
Total	4,136.97
IV. Rootplowing	0.00
V. Burning	
A. Year 1 (500 acres plus lines, 5 days)	
31-man crew ($26.48/day/man)	4,104.40
3 three-quarter ton pickup lease ($4.14/day/truck)	62.10
3 pumpers lease ($0.50/day/pumper)	7.50
Bus lease ($4.82/day)	24.10
Carryall lease ($2.59/day)	12.95
Transportation	
3 pickups ($0.135/truck/mi.) (176 mi. round trip from Phoenix)	71.28
Bus ($0.21/mi.) (170.8 mi. round trip from Phoenix via Globe, Payson)	35.87
Bus ($0.21/mi.) (20.4 mi. round trip from area to Payson) (4days)	17.14
Carryall ($0.075/mi.) (204.3 mi. round trip from Phoenix via Pleasant Valley, Payson)	15.32
Burning supplies ($0.06/acre) (500 acres)	30.00
Per diem ($10.00/day/man to camp) (21 men) (4 days)	840.00
Post fire watch (2 days)	
Pickup lease ($4.14/day)	8.28
Pumper lease ($0.50/day)	1.00
2-man crew ($26.48/day/man)	105.92
Per diem ($10.00/day/man) (2 men)	40.00
Overhead (10%)	537.59
Total	5,913.44
B. Year 2 (153 acres, 2 days)	
A similar operation to year 1. Total	2,404.11
VI. Seeding	
A. Year 1 (500 acres)	
3-man crew ($26.48/man)	79.44
Helicopter ferry ($150 hr) (3.16 hrs flight time round trip from Phoenix) (1/3)	158.00
Helicopter helper ($0.25/mi) (176 mi round trip) (1/3)	14.67
Seeding ($150/hr) (500/372 hrs)	201.61
Seed ($2.50/acre) (500 acres)	1,250.00
Pickup, three-quarter ton lease ($4.14/day)	4.14
Transportation ($0.135/mi.) (176 mi.)	23.76
Overhead (10%)	173.16
Total	1,904.78
B. Year 2 (153 acres)	
Similar to year 1. Total	796.62
VII. Herbicide (phenoxy compounds)	
A. 500 acres in years 2, 5, 11, 22, 34, 46	
3-man crew ($26.48/man)	79.44
Helicopter ferry ($150/hr) (3.16 hrs) (1/3)	158.00
Helicopter helper ($0.25/mi.) (176 mi.) (1/3)	14.67
Spraying ($150/hr) (500/372 hrs)	201.62
Spray ($2.02/acre) (500 acres)	1,010.00
Pickup lease ($4.14/day)	4.14
Pumper lease ($0.50/day)	0.50
Transportation ($0.135/mi.) (176 mi.)	23.76
Overhead (10%)	149.21
Total per year	1,641.33
B. 153 acres in years 3, 6, 12, 23, 35, 47	
Total per year	716.39
VIII. Maintenance burn	
A. 500 acres in years 4, 7, 10, 13, 17, 21, 25, 29, 33, 37, 41, 45, 49	
2-man crew ($26.48/man)	52.96
Pickup, three-quarter ton lease ($4.14/day)	4.14
Pumper lease ($0.05)	0.50
Burn supplies ($0.06/acre) (500 acres)	30.00
Transportation ($0.135) (20.4 mi. round trip from Payson)	2.75
Overhead (10%)	9.04
Total per year	99.39
B. 153 acres in years 5, 8, 11, 14, 18, 22, 26, 30, 34, 38, 42, 46, 50	
Total per year	76.48
IX. Followup seed (20%)	
A. 100 acres in year 4	
Similar to seeding except for lighter application	
Total	804.72
B. 31 acres in year 5	
Total	406.02

including the burning of firelines around part of the perimeter of the burn, will be completed by a 20-man crew. Time necessary is 4 days for 400 to 600 acres, 3 days for 200 to 400 acres, and 2 days for less than 200 acres. The seeding and subsequent maintenance burns are similar to those for Alternative I.

CONVERSION EFFECTS

Conversion impacts fall into two basic groups. The first group includes those benefits which can, with relative ease, be measured and predicted and to which a monetary value can be assigned. Increases in water runoff and forage and reduced fire hazard belong to this group. The other group includes the following less-easily quantified impacts (benefits or costs): changes in recreation use, esthetics, and wildlife habitat; soil savings or losses; and possible herbicide residue. A model will be presented for estimating yields in the first group, and a qualitative understanding will be offered for the effects in the second group.

Water Runoff

Projections of water yield increases from conversion were based on the following relationship (described in Part I) between mean annual increase in runoff ($\Delta\overline{R}$) and mean annual precipitation ($\overline{P}$):

$$\Delta\overline{R} = 0.74\overline{P} - 12.53. \quad [2]$$

A modification of this equation was necessary, however, to account for the difference between the five experimental watersheds upon which Equation 2 is based and the average conversion project. Two differences are contemplated. First, runoff increases are likely to be greater for the experimental conversions because of the more extensive and selective use of herbicides in both initial treatment and maintenance. Over 90 percent of the brush cover was removed in the experimental treatments; this study assumes a minimum of three-fourths removal of the brush in the converted portions. Second, Equation 2 represents 100 percent conversions of delineated areas, whereas a maximum of 60 percent of the 139 areas is hypothetically converted. If the untreated portion lies downslope from the converted portion, part, or possible all, of the increase may be lost to remaining chaparral plants.

Average annual water yield increase for the 139 areas was estimated by:

$$\Delta\overline{R} = 0.59\overline{P} - 10.02, \quad [3]$$

which represents 80 percent of the increase predicted in Equation 2. Mean annual precipitation ($\overline{P}$) was estimated from the map *Normal Annual Precipitation (1931-1960)* for the State of Arizona, published cooperatively by the Arizona Agriculture Experiment Station and the University of Arizona Institute of Atmospheric Physics. For example, area T13 (fig. 2), with a mean annual precipitation of 25 inches, will be expected to yield about 4.73 inches of additional runoff per year on site. If 60 percent of area T13 (1088 acres) is converted, an on-site runoff increase of 257 acre-feet is expected (0.60 x 1088 acres x 4.73 in./12 in. = 257). The average mean annual precipitation for all 139 areas is 22 inches, yielding an average on-site runoff increase for all areas of about 3 inches.

Projection Equations 2 and 3 would not apply if maintenance herbicide treatments were eliminated from Conversion Alternative I. The more tenacious sprouting species, which are found in abundance in most dense chaparral stands, can be suppressed, but not eradicated, with periodic burns (Pond and Cable 1960). Anderson and Leven predict substantial reductions in runoff as brush regrows.[8]

A portion of runoff increases is lost to evaporation and downstream vegetation. Following Hibbert and Ingebo's (1971) estimate, we assumed that 80 percent of the increased runoff would reach storage reservoirs downstream. Very little of this 80 percent is lost en route from reservoirs to actual points of use because the additional water will not measurably increase the surface area of the water traveling in the rivers or canals.

Although the hydrologic model projects average annual runoff increases, runoff increase will actually vary significantly from year to year, as does total Basin runoff. Thus, in an exceptionally dry year, the converted areas will yield little runoff increase, while in an exceptionally wet year the increase will be far above average. In the event that the downstream reservoir and canal system capacity is exceeded (which happened five times — 1941, 1965, 1966, 1968, and 1973 — in the past 50 years), and water is spilled into the Salt River, runoff increases from conversion would be lost to the full extent of the release. Furthermore, such a loss would naturally occur in a year of above average runoff. Additional storage capacity — in the form of the proposed Orme Dam, for example — would alleviate this situation.

[8] *Anderson, David A., and Andrew A. Leven. Hydrologic analysis procedures; east fork Sycamore Creek chaparral position statement. U.S. Dep. Agric., For. Serv., Southwestern Region, Albuquerque, N. Mex. Unpublished manuscript, 35 pp. 1970.*

Places of valuation. — Increases in runoff from chaparral management in the Salt-Verde Basin can be valued at three locations: (1) in streams leaving the treated watersheds, (2) at hydroelectric dams downstream, and (3) at final points of use in the Phoenix Valley or Chino Valley.

Not only greater flows, but flows for more extended periods, were observed on the Three Bar and Whitespar Experimental Watersheds following brush removal (Hibbert and Ingebo 1971). Because stream channels leaving most chaparral watersheds are dry most of the year, extending flow duration, or actually making an intermittent stream perennial, should have value to livestock and wildlife. Furthermore, additional streamflow for longer duration may enhance the recreation quality of an area. Although potentially significant, the on-site value of these runoff increases was not estimated in dollar terms.

Because part of the runoff from chaparral areas travels below the surface for some distance, the hydrologic nature of several portions of the Salt-Verde Basin is not well understood. Runoff from areas P19-P22 (fig.3) near Prescott flows into Watson Lake or Willow Creek Reservoir and is used for irrigation in Chino Valley. It seems reasonable to assume that runoff from the remaining 135 areas reaches storage reservoirs on the Salt and Verde Rivers, from where it is released to Granite Reef Diversion Dam, the outlet point for the Basin and the place where water is diverted to the agricultural, municipal, and industrial users in the greater Phoenix area. In addition, runoff increases from some areas on the Tonto National Forest flow into Roosevelt, Apache, Canyon, and Saguaro Lakes on the Salt River (fig. 2) and become available for power production as the water passes the hydroelectric dams. The methods used for determining the dollar value of the water yield increases are explained below. Irrigation water in Chino Valley is assigned the same value as water reaching the Phoenix Valley.

Value of additional water in producing power. — Additional flow through hydroelectric dams has value in replacing the most costly alternative power source. Although oil is presently the most costly alternative, coal will soon replace oil in Salt River Project power production. For this analysis we assume that the additional runoff replaces coal.

The increased runoff from 84 of the 139 chaparral areas passes through all four dams (Theodore Roosevelt, Horse Mesa, Mormon Flat, and Stewart Mountain) and has a value of $2.48 per acre-foot (1972 prices), based on data supplied by the Salt River project:

Hydroelectric dam	Value of an acre-foot of additional water
Theodore Roosevelt	$0.68
Horse Mesa	0.90
Mormon Flat	0.45
Stewart Mountain	0.45

In addition, water from two areas passes through the lower three dams, and the water from two areas passes through only Stewart Mountain Dam. The remaining 52 areas are in the Verde River Watershed.

Value of additional water below Granite Reef Dam. — The primary user of any additional water in the Phoenix Valley is the agricultural sector — there is some unmet demand for water to irrigate low-valued feed grain and forage crops. All other, higher valued demands are already met. The marginal value of additional water to the farms was $7.50 per acre-foot in 1967 (Mack 1969). Projecting to the year 2000 and assuming an increase in municipal and industrial water use of 215,000 acre-feet (O'Connell 1972a), additional water would still go to low-valued crops at a marginal value of $11.20 per acre-foot (1972 prices) (that is, the most the farmer could pay for the additional water and still pay variable costs would be $11.20).

The Salt River Valley Water User's Association (SRP) administers much of the water supply for the Phoenix Valley. Any portion of the increase not used for additional crops has value to the SRP in replacing pumped water. It would reduce pumping costs (power, operation, and maintenance costs), reduce depreciation on investment, and slow the rate of groundwater depletion. Initial increases were worth $10.30 per acre-foot in 1972 (O'Connell 1972a).

If the increase were not used for either additional crops or replacement of pumped water, it would recharge the ground water supply (as, for example, when reservoir storage capacity is exceeded), thus avoiding, to some extent, future costs of sinking wells deeper. The SRP estimates this value to be 76 cents per acre-foot. We assume for this analysis the maximum value: that all runoff increases are used to produce additional crops at a value of $11.20 per acre-foot.

Forage

Most of the 139 chaparral areas are grazed by cattle. There is evidence that these sites can produce substantial grass yields where the

chaparral is successfully controlled (Pond 1961a, b; Lavin and Pase 1963; Pase and Ingebo 1965; Tiedemann and Schmutz 1966). Chaparral-to-grass conversions may aid ranching operations on these areas in three ways: they reduce labor costs of herding by providing easier access, support more animal units per acre, and stimulate faster weight gains per animal (Pond 1967).

Lovegrasses (see Part I) are commonly used for seeding burned chaparral areas, not so much for their forage value as for the relative ease with which they become established and the watershed protection they provide. Nevertheless, if managed properly, lovegrass can be a valuable addition to many grazing allotments which rely primarily on chaparral and scattered native grasses and forbs.

Estimating increases in carrying capacity. — Each of the 139 chaparral areas was examined to estimate the value of increased cattle grazing capacity which would result from conversion to grass. Range specialists on the National Forests estimated the present grazing capacity in animal units per year (AUY) per section, and the potential forage production following conversion in pounds of forage per acre per year. These estimates corresponded with the limited results of experimental studies.

The following assumptions were necessary to estimate increases in cattle grazing with conversion:

- Forage production reaches estimated levels within three years and is maintained thereafter.
- Additional forage can be converted to pounds of beef. If the allotment is not presently overstocked, additional forage will allow an increase in the number of cattle permitted on the allotment. If the allotment is presently overstocked, additional forage will avoid a reduction in the number of cattle permitted.
- If necessary, additional fencing and water facilities will be installed to allow proper management of the converted areas.
- Since the grazing schedule is coordinated with the maintenance schedule, the converted areas will be grazed two of the first six years, four of the following six years, and 28 of the remaining 38 years (three of every four years) in the 50-year study period.
- Fifty percent of the annual growth in a chaparral pasture is utilized on slopes of less than 30 percent, while 20 percent of the annual growth is utilized on slopes of from 30 to 60 percent. Utilization by cattle of any additional forage on slopes above 60 percent is assumed to be nil.
- A 14 to 1 cow/bull ratio is maintained for any additional cattle. Furthermore, a 77 percent calf crop is assumed, with 14 percent of the cows culled each year and replaced by part of the calf crop.
- An animal unit consumes 30 pounds of air-dry forage daily.

Value of increases in grazing capacity. — Additional grazing capacity can be valuated several ways; the Forest Service grazing fee, the private lease rate, and the capitalized value are all possibilities (O'Connell 1972b). We used the "with and without" procedure, however, because it allowed area-by-area consideration of fixed cost increases. The value was defined as the difference in expected net return from cattle grazing on the areas with and without conversion.

The areas were individually examined by range specialists on the National Forests to determine if any additional fences, cattle guards, or water developments (fixed costs) would be necessary to properly manage the converted areas for grazing. Costs of these improvements depended on the characteristics of the area; the average costs were $1200 for a

mile of fence, $500 for a cattle guard, $600 for a spring development or a horizontal well, and $5000 for a vertical well (1972 prices). These improvements would be installed at the beginning of the study period. The annual annuity payment was figured using a 6-7/8 percent interest charge.

Variable costs will increase for any rancher who adds additional cattle to his operation. Costs of the following inputs or losses can be expected to increase with an increase in the size of the herd: labor, feed, veterinary services and supplies, cattle taxes, machine operation, cattle depreciation, animal death loss, and interest for the purchase of the additional animals. Costs which would not increase proportionally with additional cattle are property tax, insurance, utilities, and building depreciation. The additional variable cost of operation for an average size allotment on the Tonto National Forest — $2.94 per animal unit month (AUM) (O'Connell 1972a) — was applied to each of the 139 areas where grazing increases would be expected.

The ultimate value of additional forage is derived from the market value of the cattle produced (table 5) less transportation and sales costs. Based on ranching experience, we assumed a transportation cost of 2.5¢ per head per mile and a sales commission of $3.00 per head.

The net present value of the additional forage is the present value of the marginal annual revenues minus marginal annual variable costs and annuity on the fixed costs stemming from increased (marginal) cattle production over the 50-year study period. For the 122 areas which have a positive net present value, an average of 11 more animal units could be added per section of converted land, resulting in an average annual yield of $1.57 per converted acre and an average value per additional AUM of $6.54.

Table 5.--Estimated market value of cattle in Arizona (1972 prices)

Cattle	Average weight	Price/cwt.	Total value
	Pounds	*Dollars*	
Yearling steers	560	34.92	195.55
Yearling heifers	550	33.97	186.84
Cull cows	850	23.90	203.15

[1]Source: Prices Received by Farmers, Arizona Crop and Livestock Reporting Service, USDA and Univ. of Arizona, 5405 Federal Bldg., Phoenix, Arizona. Prices do not include transportation or sales commission.

Fire

From 1962 to 1972, 420 chaparral fires were reported on the Tonto National Forest, 137 on the Prescott. Modern quick attack techniques, utilizing air tankers that drop fire retardant on-target regardless of on-the-ground access problems, held most fires to small size. A few, however, escaped initial attack and required a large, expensive suppression effort. The Battle Fire (1972) on the Prescott National Forest, which began in dense chaparral, is a stark example. Even with the aid of essentially unlimited funds and modern equipment and firefighting techniques, the Battle Fire raged uncontrolled for 6 days, burning 14,000 acres of chaparral plus 13,500 acres of pine and mixed pine and chaparral. The suppression cost was $1.4 million dollars.

Attack methods are continually improving. The more effectively fires are controlled, however, the more fuel accumulates over time. Without significant increases in fuel managment or changes in wildfire suppression policy, additional large, expensive fires are therefore likely.

Chaparral conversion, by reducing available fuels, is one positive way of reducing the chance of large, costly fires. Proper grazing and periodic maintenance burns can effectively control accumulations of cured grasses and forbs in converted areas, reducing available fuels and lowering the average annual fire start rate. And when fires do start in converted areas, such grass fires are generally easier and less costly to control than dense chaparral fires. It should also be easier to quickly contain fires which start near converted areas, for conversions improve access and provide fuelbreaks. See Brown and Boster (1974) for a more detailed discussion of these points.

Effect of conversion on firefighting costs. — The "fire benefit" in this study is the reduction in firefighting costs as a result of conversion. Another possible benefit of fewer or smaller fires, not considered here, is a reduction in resource damages.

The model for estimating the fire benefit (Brown and Boster 1974) calculates annual firefighting cost (C) for each area (i) for the with and without conversion situations:

$$C_i = N_i \sum_k p_k c_k \qquad [4]$$

where N_i = average annual number of fires for area i

k = Forest Service fire size classes A, B, C, D, and E (all classes larger than E are included in E[9])

p_k = average proportion of fires in size class k for the 139 areas

c_k = average suppression cost of a class k fire for Basin chaparral or grass fires.

[9]*The fire size classes are defined as follows: A (up to 1/4 acre), B (1/4-10 acres), C (10-100 acres), D (100-300 acres), and E (300 acres and larger).*

The "without" minus the "with" situation gives an estimate of the average annual cost savings from conversion, which is the fire benefit. Although limitations make use of this model for estimating cost savings for individual areas risky, it is the best approach available.

One of the more likely alternatives postulated by Brown and Boster is considered here. It assumes a $45 per-acre cost of fighting class D and larger fires, and the following changes with conversion: a 20 percent reduction in fire starts, and a 50 percent reduction in the incidence of Class E and larger fires (i.e., 50 percent fewer fires will reach Class E size).

The estimated per-acre annual fire benefit for the 139 areas ranges from 3¢ to $2.00, with a mean of 31¢ and a median of 12¢. The skewed distribution of fire benefits reflects the fact that some areas have had exceptionally high fire start rates.

Recreation

Nearly all recreation use in Arizona chaparral is dispersed; developed campsites or other recreational facilities other than roads are virtually non-existant. Activities include hunting, hiking, camping, picnicking, rock hunting, sightseeing, birding, fishing, horseback riding, and driving four-wheel-drive and other vehicles for pleasure. Driving for pleasure and hunting are likely the most popular of these activities. Use is highest during the spring and fall when the climate is most agreeable.

Few chaparral areas receive much use other than hunting. Exceptions, such as Brushy Basin and Bloody Basin, are somewhat unique. Brushy Basin, part of which was converted, is accessible from Phoenix by sedan. The drive passes from southern desert shrub through chaparral to ponderosa pine. The panorama is unique, and the presence of several washes with riparian-type vegetation and the cooler pine area at the top add to the experience. Bloody Basin is part of a rugged scenic drive which includes desert shrub, chaparral, woodland, and grassland, and is also accessible by sedan. Both areas provide opportunities for hunting, camping, birding, rock hunting, and picnicking.

Except for hunting, which is spread out by the permit system, use of chaparral areas is highly dependent on the access factors — distance, travel time, and vehicle accessibility. Accessible chaparral areas relatively close to Phoenix and Globe receive considerable use since these are the closest areas providing climatic relief. More distant chaparral areas on the Tonto National Forest are used less because of the equally accessible, but more popular, ponderosa pine areas. On the Prescott National Forest, even the closest chaparral areas are no closer than the pine to the population center (Prescott), which places the chaparral areas in a secondary position for most activities.

Effect of conversion on recreation. — Three of the factors which determine recreation use — travel time and distance from population centers, vehicle accessibility, and recreational opportunities (Clawson and Knetsch 1966, p.60) — may be affected by conversion.

Vehicle accessibility increases wherever access improvements are necessary for conversion. The total supply of accessible chaparral increases if new roads are required. Travel time and distance must be considered in relation to the major sources of demand for chaparral-based recreation (Phoenix and to a lesser extent Globe). Access improvements relatively close to

these populated areas may decrease travel time to chaparral sites.

Recreational opportunities may be increased several ways. (1) If conversion improves wildlife habitat, the area may become more popular with hunters because of increased game and improved access and visibility. (2) Since conversion has been known to increase the quantity and duration of streamflow, riparian sites which receive the increased flow may experience additional recreation use. (3) In areas where chaparral is bordered by ponderosa pine, careful conversion may both provide foot access to the pine and clear the understory sufficiently to provide an attractive recreation site. (4) Conversion also opens up an area of dense brush making hiking and rock hunting more feasible.

An increase in recreation use of any particular area is either a transfer or new demand. A transfer results if an increase in visitor days for one area is offset by a decrease in visitor days at other areas. New demand represents new recreationists or an increase in recreation by former recreationists. Because of the large supply relative to demand for dispersed recreation in chaparral, much of the increase will be transfers.

Estimating change in recreation following conversion. — The District Rangers were asked their opinion of the effect of conversion on recreation use. In light of their opinions and the above considerations, the areas were ranked according to the following three categories:

1. Areas relatively close to a population center which have potential for an increase in visitor days and which also would benefit from an improvement in accessibility.
2. Areas relatively close to a population center which have potential for an increase in visitor days but need no access improvement.
3. Areas not expected to receive an increase in visitor days for one or more of the following reasons: a) lack of recreation potential, b) distance from popultion centers, c) no need for access improvements.

The 139 areas were categorized as follows:

Category:	1	2	3
Number of areas	3	7	129

The 10 areas in categories 1 (areas T33, 34, and 35) and 2 (areas T23, 24, 36, 97, 98, 100, and 109) may experience some increase in new demand as a result of conversion; demand on the other 129 areas would probably be unaffected. Area T33 (fig.2), for example, which falls in category 1, is only 48 miles from Phoenix and would require at least 3.5 miles of road improvement. Improved access would make the west side of T33 one of the closest accessible chaparral sites offering climatic relief from the desert. Increased surface runoff would improve the attractiveness of springs in the area.

Increased recreation use should be considered in any decision about conversion. The value of such an increase would have to be balanced with increased road and grounds maintenance costs caused by heavier recreation use.

Soil Loss

Some soil loss is common on most chaparral slopes. The chance of erosion is normally highest following chaparral wildfire, which not only eliminates overstory, but also reduces soil wettability and consumes much organic matter on the soil surface (see Part I).

Initially, chaparral conversion also increases the chance of erosion, but probably not as much as wildfire. Chemical and mechanical eradication should have less effect than prescribed burning.

Present evidence suggests two conclusions about the effect of conversion on soil loss (based on Part I). (1) Conversion to grass should not allow more erosion than natural chaparral, assuming a good grass stand is established. (2) In the long run, conversion should reduce erosion because the wildfire cycle will be interrupted and heavy post-fire erosion avoided. Both conclusions require that management after conversion must insure both maintenance of the grass stand and proper grazing procedures.

Wildlife

Most wildlife specialists agree that carefully planned and executed conversions can improve wildlife habitat. Part I lists the following improvements as possible results of conversion: (1) Space is provided for animal movement by opening up dense brush stands, (2) abundance and quality of browse and forage are augmented, and (3) variety of food is increased.

The following three qualifications are often listed by wildlife specialists regarding chaparral conversion (Part I): (1) Conversions should be limited to the more dense, continuous stands, especially those dominated by relatively unpalatable species such as shrub live oak, (2) a maximum of 50 percent of a stand should be converted, and (3) the converted portions should be small and spread throughout the original stand.

The 60 percent conversion postulated here for most areas is more extensive than that generally recommended by wildlife specialists. While not ideal, however, such conversions would alter the more dense chaparral stands which presently impede animal movement, and, if properly executed and maintained, should create a desirable patchwork of converted and non-converted areas.

Esthetics

The esthetic appearance of a conversion project is, of course, a matter of opinion and time. The important opinion is that of the public, and, unfortunately, nothing has yet been reliably determined about public perception of chaparral conversion. Research is needed to set down guidelines for the most esthetically pleasing design. The time factor affects all vegetation management practices. Is the public willing to put up with a temporary, say 5-year, degradation to receive a long-term improvement?

The following variables influence the esthetic appearance of a conversion:

- The size of the converted area.
- The area's shape — how well the shape fits the topography.
- The spacing of various clearings.
- The well-placed presence of small relict areas within a larger conversion.
- The area's proximity to roads and fences.

It is easier to create a pleasing pattern (assuming landscape architects can design one) with rootplowing or herbicides than with fire. In rootplowing, the topograpohy, depth of soil, and presence of large rocks are the only constraints, while with carefully applied herbicides there are essentially no constraints. Particular bushes, clumps of bushes, or large areas can either be removed or left standing. Fire, however, is not as easily controlled. As the desired pattern becomes more meticulous, the cost of the burning increases, with no definite guarantee that a relict area will actually be saved.

In this study a somewhat more realistic approach is taken in Conversion Alternative I. Larger portions are burned than would be ideal from the esthetic standpoint. The fire will determine which areas, if any, will initially be left within broad boundaries consisting of from 100 to 600 acres. Selective seeding and maintenance will later be used to establish a desired pattern. If a patch is not seeded or sprayed, the brush will soon take over and the patch will not readily burn for many years. Thus, while the desired pattern is not immediately created, it develops with time.

No attempt will be made to quantify the effect of conversion on esthetics. It does appear, however, that a properly planned conversion will make the landscape more attractive within a few years.

Herbicide Use

Although experience suggests that herbicides are necessary for successful chaparral conversions, their future use will depend on forthcoming Environmental Protection Agency regulations governing herbicide use.

None of the soil-applied herbicides which have been tested for brush control are presently registered for management use. Also, it is not known how new regulations covering the use of broadleaf herbicides presently registered for range use will affect their use on watershed lands. (See the pesticide precautionary statement on the inside back cover). New regulations should set standards to guard against unacceptable levels of environmental contamination. Any environmental damage due to herbicide usage, however, would represent a cost of conversion over and above application costs.

INTEGRATION OF BENEFITS AND COSTS

Benefit-cost analysis (Howe 1971), which was used to compare the present values of the quantified benefits and costs, provides two fundamental indices of project worth, the benefit-cost ratio (B:C) and the benefit-cost difference (B-C). B:C is a measure of the economic feasibility of a proposed project; an area is economically feasible for conversion if the ratio of the present value of its benefits (B) to the present value of its costs (C) is greater than 1.0. B-C gives a measure of the magnitude of the net benefit, or loss, obtainable from the project. As explained in the introduction, present values were calculated using a 6-7/8 percent discount rate.

Results for Conversion Alternatives I and II

The benefit-cost analysis of Alternative I (initial burn with maintenance burns and herbicide sprays) indicates that conversion is economically feasible on 96 of the 139 areas, which contain 82 percent (273,383) of the total delineated acres and 83 percent (147,118) of the actual conversion acres (table 6). Seventy-eight of the economically feasible treatment areas are on the Tonto National Forest and 18 are on the Prescott. Most feasible treatment acreages are on the Globe, Mesa, Payson, Pleasant Valley,

Roosevelt and Walnut Creek Ranger Districts (table 7).

For Alternative II (initial soil-applied herbicide treatment with maintenance burns), conversion is economically feasible on 72 of the 139 areas (table 6), which encompass 58 percent of the total acreage and 60 percent of the actual conversion acreage. The greater initial treatment costs for Alternative II, as compared with Alternative I, resulted in fewer areas meeting the economic criterion.

Benefit-cost ratios for Alternative I range from 0.1 to 6.4. Forty-seven areas have a B:C greater than 2.0 and 15 areas have a B:C greater than 3.0 (table 7). The range for Alternative II is considerably narrower — from 0.1 to 3.2, and only nine areas have a B:C greater than 2.0. Benefit-cost ratios and differences for each area are listed in the Appendix.

Of the three conversion benefits which we quantified, water runoff increases proved the most significant economically. Runoff increases yielded more, in present value terms, than forage or fire benefits on 98 of the areas. Forage benefits yielded most return on 29 areas, and fire benefit on 12 areas. Assuming Alternative I, estimated runoff increases actually cover conversion costs for 61 areas, while forage increases cover costs on 21 areas and reductions in wildfire suppression costs cover costs on eight areas.

Table 6.--Portion of total delineated acreages with a benefit-cost ratio[1] greater that 1.0 for alternative conversion schemes, 139 chaparral areas, Salt-Verde Basin, Arizona

Alternatives	Areas		Size	
			Total	Actual conversion[2]
	Number	*Percent*	*Acres*	
Alternative I				
Best estimate	96	69	273,383	147,118
Low estimate[3]				
Water runoff	94	68	264,210	143,703
Forage production and utilization	81	58	208,709	113,664
Fire benefit	89	64	264,431	144,233
Combined low estimate	64	46	186,993	103,740
Alternative II	72	52	192,796	106,543

[1]Constant 1972 dollars over 50-year planning horizon discounted at 6-7/8 percent.
[2]The 60 percent or less of each area which was considered the part actually treatable.
[3]Each of the three quantified benefits were individually reduced to their lowest reasonable estimate (one yield was reduced while the other two remained at the "best estimate" level).

Table 7.--Distribution (by Ranger District for Conversion Alternative I) of areas economically feasible for conversion, Salt-Verde Basin, Arizona

Forests and Districts	Areas with benefit-cost ratio[1] greater than--					
	1.0		2.0		3.0	
	No.	*Acres*[2]	*No.*	*Acres*[2]	*No.*	*Acres*[2]
Tonto						
Cave Creek	4	8,569	1	1,382	-	-
Globe	12	22,288	8	12,867	1	2,695
Mesa	10	14,725	4	10,900	1	1,579
Payson	15	23,015	12	20,131	6	10,688
Pleasant Val.	23	22,714	15	78,236	6	6,298
Roosevelt	14	22,895	7	18,238	1	1,477
Sub-total	78	114,206	47	81,754	15	22,737
Prescott						
Chino Valley	1	2,552	-	-	-	-
Thumb Butte	6	2,988	-	-	-	-
Verde	2	1,336	-	-	-	-
Walnut Creek	9	26,036	4	12,538	1	6,797
Sub-total	18	32,912	4	12,538	1	6,797
Total	96	147,118	51	94,292	16	29,534

[1]Constant 1972 dollars over 50-year planning horizon discounted at 6-7/8 percent.
[2]Actual conversion acreage (a maximum of 60 percent of each area).

Modification of Benefits for Conversion Alternative I

The results of the benefit-cost analysis of Alternatives I and II are based on the best estimate of expected changes in runoff, forage production and utilization, and incidence of large wildfires following conversion. Because

these benefits are less than certain, however, we also calculated the benefit-cost analysis of Alternative I using the lowest reasonable estimates of the above benefits. Specifically, (1) runoff increases were estimated to be 30 percent less than those experienced on experimental watersheds, rather than 20 percent; (2) maximum lovegrass production was assumed to be 900 pounds per acre, rather than 1500 pounds, and forage utilization was lowered from 50 percent to 35 percent on slopes less than 30 percent, and from 20 percent to 10 percent on slopes of from 30 to 60 percent; and (3) the proportion of Class E and larger fires remains the same with conversion as without, rather than being reduced by 50 percent.

Separate incorporation of the low estimates of the water, forage, and fire yields (reducing one yield while maintaining the other two at the "best estimate" level) reduced the number of areas with B:C greater than 1.0 from 96 to 94, 81, and 89 respectively. If the low estimates are assumed for all three yields, conversion is economically feasible for only 64 areas (table 6 and Appendix).

Maximum Potential Benefits

We do not suggest that all areas found here to be economically feasible for treatment should actually be converted. Each area must be examined in detail. Economic efficiency is not the sole determinant in land management decisions. Nevertheless, it is instructive to examine the range of feasible benefits from conversion.

If all 96 areas with B:C greater than 1.0 (Alternative I) were converted (an actual conversion of 147,118 acres, table 6) an average of 30,443 acre-feet of additional water would become available for downstream users each year. In addition, cattle grazing capacity would increase by an average of 35,520 AUM per year, and average annual firefighting costs should be reduced by $90,289. The gross annual benefits would be less under Alternative II, or the reduced version of Alternative I (table 8).

These values should be compared with averages of 1.2 million acre-feet of runoff which annually reaches storage reservoirs in the Salt-Verde Basin, 980,000 AUM annually carried by the Basin, and about $3 million annually spent for fire protection and suppression in the Basin. In other words, actual conversion of 147,118 acres of chaparral (1.8 percent of the Basin) could potentially increase Basin runoff reaching reservoirs by 2.5 percent, increase cattle grazing capacity 3.6 percent and reduce Forest Service firefighting costs in the Basin by 3.0 percent.

Subtracting the annuity[10] of the 50-year conversion and maintenance cost stream for an area from the annuity of the 50-year benefit stream for that area gives the net annual return from conversion. The total net annual return from conversion of all areas with a benefit-cost ratio greater than 1.0 (Alternative I) would be $369,347 (table 8).

Table 8.--Total impacts of conversion[1] of all areas with benefit-cost ratio[2] greater than 1.0, Salt-Verde Basin, Arizona

Impacts	Alt. I (best estimate)	Alt. I (low estimate)[3]	Alt. II
Average annual benefits			
Water			
Increase in off-site[4] runoff (acre-feet)	30,443	24,010	27,281
Value to agric. ($)	340,960	268,907	305,551
Value to power ($)	43,494	36,721	41,766
Total water value ($)	384,454	305,628	347,317
Forage			
Increase in grazing capacity (AUM)	35,520	5,883	25,608
Value ($)	265,710	26,146	189,076
Fire			
Value ($)	90,289	35,082	76,775
Annuity of benefits ($)	661,182	346,503	552,660
Annuity of costs ($)	291,835	202,238	352,660
Net annual benefits ($)	369,347	144,265	199,687

[1]Changes due to conversion, measured by the "with minus the without" technique.
[2]Constant 1972 dollars over 50-year planning horizon discounted at 6-7/8 percent.
[3]Alternative I reduced by using low estimates of yields of water runoff, forage production and utilization, and fire benefits.
[4]Eighty percent of the estimated on-site runoff increase.

Average Conversion Impacts

If all 96 chaparral areas economically feasible for treatment under Alternative I were actually converted, a yearly average of 0.21 foot per acre of additional downstream runoff could be expected from the converted portions. Likewise, an average annual increase of 0.24 AUM per acre and a decrease of $0.34 in firefighting costs per acre could be expected. These three impacts yield a gross average annual (annuity) return of $4.49 per acre. Subtracting average per-acre (annuity) conversion costs of $1.98 leaves a net average annual return of $2.51 per acre. The range of this net return for all 96 areas is from $0.04 to $6.89 (table 9).

Assuming the low estimates of runoff, forage, and fire benefits for Alternative I, conversion of the 64 areas economically feasible for treatment would yield a gross average annual return of $3.34 per acre. The annuity of average per-acre costs for these areas is $1.95, and the net average annual return is $1.39 per acre (table 9).

[10]*Annuity* $= PV\,[i(1+i)^t/((1+i)^t-1)]$, *where PV is present value, i is the discount rate, and t is time in years.*

Assuming Alternative II (and the best estimates of the benefits), gross average annual return is $5.18 for the 72 economically feasible treatment areas. The annuity of average per-acre costs, however, is also higher — $3.53 — leaving a net average annual per-acre return of $1.87 (table 9).

The non-value-determined impacts of conversion are less easily predicted. Recreation use should increase for some areas, but will probably be unaffected on most. With proper grazing management, long-term soil loss should lessen with conversion or be similar to without conversion; with improper grazing, soil loss would probably increase. Careful treatment and maintenance should create a wildlife habitat superior to dense chaparral. Conversion without regard for pattern, however, may harm wildlife habitat. Finally, depending on the particular qualities of the chaparral area and the care taken in creating patterns, conversion will either improve or harm the area's esthetic appearance (table 9).

Importance of Some Major Assumptions

Numerous assumptions were necessary to estimate conversion costs and benefits. Six important assumptions — concerning the discount rate, the effects of inflation, conversion on steeper slopes, access requirements, fire policy, and areas under special agreements — are examined here.

Discount rate. — Although the Water Resources Council is presently recommending use of a 6-7/8 percent discount rate, it has also recognized that the real rate of return on non-Federal investment is about 10 percent (U.S. Water Resources Council 1971). Use of the lower rate in evaluating projects with large investment costs may show a benefit-cost ratio greater than 1.0 while use of the higher rate would not. Many economists argue (Cicchette, et al. 1973, for example) that the higher rate, being the opportunity cost of Federal investment, is more appropriate. Implementation of a project efficient at a 6-7/8 percent discount rate but inefficient at a 10 percent rate in effect represents a regional subsidy.

Increasing the discount rate from 6-7/8 to 10 percent reduces the number of areas economically feasible for Alternative I conversion (best estimates of the benefits) from 96 to 79. These 79 areas encompass 229,727 total acres and 126,944 possible conversion acres.

Probable effects of inflation on study results. — In the introduction we assumed that inflation would have similar relative impacts on benefits and costs. In the past year (1973), however, prices of food products and fuel rose considerable faster than all other commodities. Specifically, prices of feed grains and feeder cattle rose 50 percent faster than farm production costs or conversion costs (U.S. Dept. of Commerce 1974). Is this relative advantage merely temporary, or a long-term change?

Table 9.--Average annual impacts of conversion[1] for chaparral areas with a benefit-cost ratio[2] greater than 1.0, Salt-Verde Basin, Arizona

Impacts	Alternative I (best estimate)		Alternative I (low estimate)		Alternative II	
	Average	Range[3]	Average	Range[3]	Average	Range[3]
Value-determined impacts (per converted acre)						
Water (acre-feet off-site)	0.21	0.00- 0.43	0.23	0.11-0.35	0.26	0.03- 0.43
Forage (AUM)	.24	.00- .45	.06	.00- .16	.24	.07- .38
Fire ($)	.34	.02- 2.00	.19	.01-1.49	.40	.02- 2.00
Economic effects[4]						
Gross return ($)	4.49	1.92-10.91	3.34	1.75-7.64	5.18	2.35-10.91
Cost ($)	1.98	1.28- 8.84	1.95	1.25-5.97	3.31	2.66- 9.62
Net return ($)	2.51	.04- 6.89	1.39	.10-3.34	1.87	.03- 5.74
Non-value-determined impacts[5]						
Recreation	----------some areas +, others 0----------					
Soil	0 or + with proper management, - with improper management					
Wildlife habitat	+ with proper management, - with improper management					
Esthetics	----------could be + or minus----------					

[1]Refers to the change with conversion, i.e., the with minus the without case.
[2]Constant 1972 dollars over 50-year planning horizon discounted at 6-7/8 percent.
[3]For some cases, extreme points were not reported.
[4]Expressed as annuity.
[5]Long-term average impacts.

Past experience suggests that this relative difference, in large part at least, will be short-lived. First, both wage earners and the business community have already begun to regain their former relative economic position by seeking wage and price increases. This means that the cost of labor, equipment, and materials to the farmer and rancher, as well as those to implement chaparral conversion and maintenance, will increase relative to feed grain and feeder cattle prices. Second, the farm products industry should, as it has in the past, respond to relative increases in the prices of its products with increased production, thereby diminishing the short-term price increases.

The new increase in foreign demand for our agricultural products, concurrent with devaluation and rising affluence abroad, was in part responsible for domestic price increases in farm products. It is impossible to determine the future course of foreign demand accurately. The best prediction at this time is that a large portion of the 50 percent increase in farm product prices relative to all other commodities will dissipate in the long run.

Since the net benefit of fire hazard reduction was based on differences between costs of conversion and costs of fire suppression, the relative difference should remain constant. The same conclusion applies to water if the replacement value of pumping is used, rather than ability to pay.

Conversion on steeper slopes. — The steeper the slope, the more difficult access becomes, the greater the potential for soil loss, and the smaller the increase in cattle carrying capacity. Conversion has been quite successful on the Three Bar Experimental Watersheds on slopes near 60 percent, however, and potential soil loss from a prescribed burn is generally less than from a wildfire. Nevertheless, the gentler slopes should receive preference.

Only 33 percent of the 332,796 acres covered by the 139 chaparral areas is on slopes of less than 30 percent. A reduction in the slope steepness criterion from 60 to 30 percent would affect some areas very little (such as those in Chino Valley and Thumb Butte Ranger Districts), but the treatable acreage on others, with a large portion of relatively steep slopes (such as those in Mesa and Roosevelt Ranger Districts), would be reduced considerably (table 1). The estimated treatment acreage in the 96 areas economically feasible for Alternative I conversion would be reduced by 37 percent to 93,235 acres.

Access requirement. — The lack of vehicular access to some of the possible conversion areas may influence the decision of whether or not to convert an area. Although accesss improvements increase firefighting efficiency, they also increase the chance of man-caused fire starts. In some cases, access improvements may conflict with the overall management plan for the area.

Several National Forest "roadless areas" have recently been proposed that include 10,720 acres in 13 of the 139 delineated chaparral areas. Exclusion of these areas from consideration for conversion would eliminate all or part of 10 of the 96 areas with B:C greater than 1.0 (Alternative I).

Limitations on access improvements could significantly restrict conversion possibilities. Half of the 96 areas with a B:C greater than 1.0 (Alternative I) require some accesss improvement for conversion. Eleven of these areas require a stretch of new road and nine additional areas require extensive primitive road improvements.

Fire policy. — Calculation of the "fire benefit" assumed continuation of present fire suppression and fuel management practices. In light of concerted fire suppression and minimal fuel management, conversion can significantly alleviate hazardous fuel situations and reduce firefighting costs. A change in suppression practices which allowed more fires to burn themselves out would reduce firefighting costs, and with them the estimated fire benefit.

Increases in prescribed burning, without subsequent efforts to maintain a grass stand and suppress shrub regrowth, would also affect the fire benefit. Less expensive than conversion, it would be more effective in reducing firefighting costs and would also be more acceptable to wildlife interests. If prescribed burning for fuel management were extensively practiced, the "fire benefit" of conversion would be minimal.

Experimental watersheds. — Seven of the 139 chaparral areas are presently held under special agreements. All had B:C ratios greater than 1.0. Their exclusion from consideration for conversion would reduce the number of areas economically feasible for Alternative I conversion to 89.

SUMMARY AND CONCLUSIONS

Chaparral covers approximately 850,000 acres on National Forest land in the Salt-Verde Basin. Over 500,000 acres have no potential for conversion because they are (1) in or adjacent to wilderness areas, (2) of less than 30 percent cover, or (3) on slopes greater than 60 percent. On the basis of specified cover, slope, and operational criteria, 332,796 acres, in 139 designated areas, were considered worthy of consideration for conversion.

The 139 areas were analyzed on the following operational premises:

- Herbicide use for conversion is acceptable (only time will tell if this premise is valid).
- Areas are successfully converted to grass.
- Proper grazing management follows conversion (thereby avoiding undue erosion).

To allow for establishment of a pattern of chaparral and grass acceptable from the wildlife and esthetics standpoints, we assumed that a maximum of 60 percent of a delineated area could actually be converted to grass. This assumption reduced the maximum acreage considered for conversion to 175,912 acres. Of this, 124,786 acres (71 percent) are on the Tonto and 51,126 (29 percent) are on the Prescott National Forest.

The 139 delineated chaparral areas represent the maximum chaparral available for conversion on National Forest land in the Salt-Verde Basin. Additional criteria — physical (soil, slope, or wildlife habitat), managerial (access requirements or grazing management problems), or economic (efficiency or budgetary constraints) — will reduce the maximum. We evaluated the economic efficiency of converting the 139 areas by means of benefit-cost analysis.

Costs and benefits of converting each of the 139 delineated areas were estimated for a 50-year time horizon. Treatment and maintenance costs were estimated for two conversion alternatives based on Forest Service experience. Costs of an Environmental Impact Statement, providing access, installing fuelbreaks and firelines, rootplowing, burning, seeding, and maintaining the conversion with burning, broadleaf herbicides, and partial seeding were calculated for Alternative I. Alternative II is similar to Alternative I, but modifies the fuelbreak-fireline requirement, replaces initial burning with a soil-applied herbicide, and eliminates herbicide maintenance. On the benefit side, the effects of conversion on runoff, forage production, and firefighting costs were estimated. A monetary value was put on the incremental yields, and the present values of the benefits and costs were compared in a benefit-cost ratio.

Three important assumptions were made for the economic analysis. First, a 6-7/8 percent discount rate was used. Second, we assumed that all increased runoff reaching the Phoenix Valley would be used for increasing agricultural production. Third, we assumed that the relative position of prices would not change over the long run.

For Alternative I, chaparral conversion was found to be economically feasible (benefit-cost ratio greater than 1.0) for 96 of the 139 delineated areas. These 96 areas contain a total of 273,383 acres on the Tonto and Prescott National Forests, 54 percent of which (147,118 acres) was considered the amount actually convertible. For Alternative II, costs increase such that only 72 areas, encompassing 106,543 actual conversion acres, are economically feasible for conversion.

Conversion Alternative I was also evaluated with the low, rather than the best, estimates of water, forage, and fire benefits. In this case 64 of the 139 areas, containing a total of 103,740 actual conversion acres, were found economically feasible for conversion.

If all 96 economically feasible areas were to be converted by Alternative I, the following average annual benefits could be expected: 0.21 foot of additional runoff downstream from each converted acre, 0.24 additional animal unit months per converted acre, and a 34 cent reduction in firefighting costs per converted acre. The

average per-acre annuity benefit ($4.49) minus the annuity cost ($1.98) leaves a net average annual return of $2.51 per converted acre. The total yields from conversion of 96 areas could potentially increase Basin runoff by 2.5 percent, increase Basin cattle carrying capacity by 3.6 percent, and decrease Basin firefighting costs by 3 percent. These yield increases are based on the best estimates of the benefits. Results for Alternative II, or for Alternative I with the low estimates of the benefits, are less optimistic.

Several non-quantified, non-value-determined impacts were also examined. Recreation use should increase in a few areas following conversion, but will probably be unaffected in most areas. Effects on soil movement, wildlife habitat, and esthetics will depend on the manner in which treatment and maintenance are carried out; proper management should favorably affect these values.

Although chaparral conversion was shown to be economically beneficial for some areas, this does not necessarily mean that they should be converted. More detailed analyses, utilizing additional criteria and on-site investigation, are of course required on a per-area basis. Furthermore, future consideration of benefits or costs, either primary or secondary, which were not quantified in this analysis, may change the results. Also, and most far-reaching, this study deals only with conversion; opportunity costs were not considered. Other uses of limited funds may supercede their use for chaparral conversion.

A comprehensive economic analysis such as this helps put the potential of chaparral conversion in perspective. By comparing all chaparral lands in the entire study area, the possibilities of future chaparral conversion in general are presented for the land manager and others to view. The rough estimates of the costs and benefits discourage both over-optimistic and over-pessimistic views of the program. Such a broad perspective is often very useful in determining the directions of future policy.

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APPENDIX

Table 10.--Location, size, and benefit-cost results for 139 chaparral areas in the Salt-Verde Basin, Arizona.

Area[1]	Ranger District[2]	Size		Benefit-Cost ratio 5/			Benefit minus cost 9/ (best estimate)
		Total[3]	To be 4/ convert.	Alt.I 6/ (best estimate)	Alt.I 7/ (low estimate)	Alt.II 8/	
		----Acres------					$
1	CC	3,203	1,922	1.02	0.59	0.58	1,141
2	CC	2,304	1,382	2.04	1.13	1.11	87,294
3	CC	3,200	1,920	1.92	1.14	1.13	51,668
4	CC	8,354	3,342	1.22	.74	.65	16,064
5	CC	4,076	2,446	.79	.04	.29	-22,152
6	P	4,160	2,496	1.36	.65	.78	22,538
7	P	512	307	2.53	1.57	1.80	18,940
8	P	200	120	1.09	.76	.93	772
9	P	2,592	1,555	2.16	1.52	1.22	50,465
10	P	3,281	1,969	2.56	1.69	1.43	78,479
11	P	2,746	1,648	3.05	1.89	1.84	98,019
12	P	3,136	1,882	2.80	1.65	1.71	95,463
13	P	1,088	653	3.41	1.95	2.21	55,177
14	P	3,238	1,943	6.40	4.13	3.21	243,171
15	P	2,429	1,457	2.72	1.73	1.63	70,899
16	P	448	269	1.16	.75	1.05	2,635
17	P	189	113	.54	.38	.50	-5,850
18	P	3,789	2,273	2.69	1.64	1.60	94,725
19*	P	3,564	1,426	3.19	1.81	1.80	83,960
20	P	6,183	2,473	3.88	2.34	2.04	165,550
21	P	6,365	2,546	3.15	1.87	1.67	126,774
22	P	640	384	.49	.38	.39	-12,521
23	M,R	7,751	4,651	2.59	1.80	1.47	165,903
24	M	5,180	3,108	2.08	1.56	1.17	85,121
25	M	250	150	.77	.67	.65	-2,145
26	M	384	230	1.28	.89	1.01	3,130
27	R	3,002	1,801	2.42	1.75	1.45	74,132
28	M,R	2,632	1,579	3.02	2.00	1.85	91,051
29	R	184	110	.44	.39	.44	-9,157
30	M,R	3,379	2,027	2.44	1.60	1.50	84,207
31	R	448	269	.67	.54	.51	-4,063
32	R	220	132	1.27	.87	1.35	2,890
33	M,R	4,995	2,997	2.47	1.66	1.49	117,628
34	M	6,976	4,186	2.39	1.62	1.33	134,537
35	M,R	1,735	1,041	1.68	1.22	1.08	24,438
36	R	8,418	5,051	2.61	1.87	1.41	165,214
37	M	352	211	1.46	.99	1.28	6,460
38	R	320	192	.23	.20	.21	-10,777
39	M	1,856	1,114	.19	.70	.73	7,074
40	M	----------Brushy Basin----------					
41*	R	2,462	1,477	4.30	2.92	2.26	118,765
42*	R	706	424	1.66	1.08	1.35	13,395
43	M	800	480	.88	.69	.74	-4,281
44	M	1,344	806	1.14	.82	.89	7,500

Table 10. continued

Area[1]	Ranger District[2]	Size		Benefit-Cost ratio 5/			Benefit minus cost 9/ (best est.)
		Total[3]	To be 4/ convert.	Alt.I 6/ (best estimate)	Alt.I 7/ (low estimate)	Alt.II 8/	
		---- Acres -----					$
T 45	M	704	422	1.38	.94	1.17	10,875
T 46	M	224	134	.56	.42	.53	-8,809
T 47*	R	1,920	1,152	1.80	1.22	1.15	32,268
T 48*	R	2,902	1,741	1.75	1.06	.99	35,019
T 49	M	256	154	.83	.53	.77	-3,173
T 50*	R	650	390	1.12	.61	.81	2,298
T 51	PV	384	230	.82	.64	.74	-2,924
T 52	P,PV	704	422	.44	.34	.37	-16,238
T 53	PV	448	269	.56	.34	.48	-12,607
T 54	PV	1,088	653	.83	.60	.64	6,791
T 55	PV	2,432	1,459	2.08	1.38	1.30	53,833
T 56	R	2,432	1,459	2.31	1.64	1.42	62,774
T 57	PV	3,692	2,215	2.80	1.95	1.60	110,541
T 58	PV	3,119	1,871	2.87	1.91	1.57	90,652
T 59	PV	384	230	1.33	.97	1.16	4,963
T 60	PV	1,216	730	2.67	1.73	1.80	44,485
T 61	PV	128	79	.67	.61	.69	-4,339
T 62	PV	832	499	3.58	2.97	2.54	46,518
T 63	R	704	422	1.52	1.24	1.44	9,038
T 64	PV	1,280	768	2.55	1.68	1.72	48,253
T 65	PV	192	115	1.23	.99	1.13	3,341
T 66	PV	1,126	730	3.57	2.29	2.47	78,429
T 67	PV	635	381	3.62	2.08	2.47	36,818
T 68	PV	1,145	687	1.73	1.01	1.14	19,406
T 69	PV	3,680	2,208	3.18	1.98	1.98	99,354
T 70	PV	4,595	1,838	2.94	1.79	1.64	133,579
T 71	PV	960	576	2.46	1.68	1.74	32,392
T 72	PV	1,616	970	3.35	2.38	1.93	65,894
T 73	PV	2,816	1,408	2.63	1.74	1.55	70,856
T 74	PV	2,683	1,342	1.35	.92	.89	17,103
T 75	PV	96	58	.88	.66	.87	-1,195
T 76	PV	88	53	1.15	1.06	1.12	1,128
T 77	PV	192	77	.74	.70	.73	-3,962
T 78	PV	448	179	1.85	1.49	1.59	11,485
T 79	PV	256	154	2.04	1.87	1.89	13,401
T 80	PV	5,970	1,493	1.06	.80	.66	2,815
T 81	PV	723	434	.89	.47	.66	-2,066
T 82	PV	632	379	1.36	.71	1.05	7,629
T 83	R	1,336	802	2.61	1.70	1.78	49,741
T 84*	PV	3,745	2,247	3.15	2.18	1.84	129,356
T 85	R	792	396	1.50	1.08	1.08	7,265
T 86	G	1,280	768	.83	.40	.54	-4,777
T 87	G	448	179	.94	.89	.80	-613
T. 88	G	5,632	2,253	1.30	.40	.75	16,466

Table 10. Continued

Area[1]	Ranger District[2]	Size		Benefit-Cost ratio 5/			Benefit minus cost 9/
		Total[3]	To be 4/ convert.	Alt.I 6/ (best estimate)	Alt. I 7/ (low estimate)	Alt.II 8/	(best est.)
		--- Acres ------					$
T 89	G	1,632	653	2.92	1.73	1.83	42,408
T 90	G	6,720	2,688	1.50	.48	.79	30,972
T 91	G	5,696	3,418	1.55	.58	.91	43,095
T 92	G	192	115	.64	.28	.54	-2,905
T 93	G	2,976	1,190	.11	.01	.06	-33,541
T 94	G	704	422	.46	.15	.32	-8,240
T 95	G	448	269	.46	.27	.35	-6,435
T 96	G	2,186	874	.15	.01	.09	-26,503
T 97	G	2,432	973	2.36	1.12	2.31	38,969
T 98	G	1,216	486	.78	.21	1.01	-4,490
T 99	G	128	51	.24	.11	.24	-6,911
T100	G	320	128	.74	.23	.57	-1,965
T101	G	384	154	.12	.11	.10	-10,409
T102	G	216	108	.44	.39	.40	-6,771
T103	G	2,656	1,062	1.76	1.62	1.15	29,903
T104	G	4,680	1,872	2.61	2.08	1.43	75,791
T105	G	2,480	992	2.13	1.66	1.34	38,127
T106	G	1,563	625	2.01	1.46	1.31	23,686
T107	G	4,492	2,695	3.68	2.33	2.08	177,825
T108	G	1,920	1,152	2.10	1.34	1.36	43,883
T109	G	6,508	3,905	2.71	1.43	1.59	155,747
P 1	WC	1,952	781	.21	.10	.16	-28,011
P 2	WC	3,424	2,054	2.10	.95	1.28	65,890
P 3	WC	1,523	914	.62	.04	.47	-11,837
P 4	WC	2,720	40	1.45	1.17	.99	18,298
P 5	WC	704	422	2.49	1.45	1.85	29,231
P 6	WC	5,440	3,264	2.04	1.07	1.19	88,068
P 7	WC	11,328	6,797	3.26	1.40	1.67	269,934
P 8	WC	12,160	7,296	1.59	.06	.84	76,764
P 9	WC	1,248	624	.80	.33	.53	-6,339
P 10	WC	2,611	1,306	1.72	.97	1.03	33,181
P 11	WC	2,924	1,754	1.31	.05	.70	14,569
P 12	WC	3,424	2,054	1.70	.21	.89	36,036
P 13	TB	1,024	307	.25	.07	.15	-13,062
P 14	TB	1,984	595	.43	.12	.24	-12,145
P 15	TB	352	211	.68	.19	.46	-5,006
P 16	TB	3,776	1,133	1.23	.13	1.04	8,276
P 17	TB	1,664	832	1.40	.57	.93	11,772
P 18	TB	576	230	.76	.52	.42	-3,199
P 19	TB	576	230	1.31	.81	.61	3,569
P 20	TB	704	141	1.47	.75	.82	5,680
P 21	TB	480	288	1.72	.94	.78	9,485
P 22	TB	608	365	1.56	.97	.77	10,046

Table 10. Continued

Area[1]	Ranger District[2]	Size		Benefit-Cost ratio 5/			Benefit minus cost 9/ (best est.)
		Total[3]	To be 4/ convert.	Alt.I 6/ (best estimate)	Alt. I 7/ (low estimate)	Alt.II 8/	
		-----Acres-----					$
P 23	V	1,536	922	1.59	1.37	.78	18,198
P 24	V	1,382	415	1.28	1.06	.59	5,474
P 25	V	384	192	.52	.41	.19	-6,199
P 26	CV	192	115	.28	.17	.13	-13,327
P 27	V	7,359	4,415	.28	.24	.13	-69,451
P 28	V	3,968	2,381	.41	.01	.21	-36,572
P 29	V	7,616	4,570	.02	.01	.01	-98,121
P 30	CV	4,255	2,553	1.10	.59	.56	6,810
P 31	V	9,581	2,876	.65	.56	.34	-27,898

1/ Numbers of areas in Fig. 2 (Tonto National Forest) are preceded by "T"; numbers of areas in Fig. 3 (Prescott National Forest) are preceded by "P". Starred (*) areas are presently held under a special management agreement.

2/ Ranger Districts on the Tonto are Cave Creek (CC), Globe (G), Mesa (M), Payson (P), Pleasant Valley (PV), and Roosvelt (R). Districts on the Prescott are Chino Valley (CV), Thumb Butte (TB), Verde (V), and Walnut Creek (WC).

3/ The total acreage of the area minus any private property in the area.

4/ The portion of the area (60 percent or less) estimated to be convertible.

5/ Discount rate is 6-7/8 percent.

6/ Conversion Alternative I: initial burn with maintenance burns and broadleaf herbicide sprays.

7/ Alternative I but based on the low, rather than the most likely, estimates of the water, forage, and fire benefits.

8/ Conversion Alternative II: initial soil-applied herbicide with maintenance burns.

9/ Present value of benefits minus present value of costs for Alternative I at 6-7/8 percent.

Brown, Thomas C., Paul F. O'Connell, and Alden R. Hibbert
1974. Chaparral Conversion potential in Arizona. Part II: An economic analysis. USDA For. Serv. Res. Pap. RM-127, 28 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Is chaparral conversion on National Forests in the Salt-Verde Basin economical? An inventory revealed 139 chaparral areas totaling 332,796 acres meet certain crown cover, slope, and managerial criteria for conversion. The costs of converting portions of these areas to grass and maintaining the conversion over a 50-year period were compared with the benefits to society in terms of increased water yield and forage for livestock, and reduced firefighting costs. Using fire as the main conversion tool, 96 areas have a benefit-cost ratio greater than 1; using a soil-applied herbicide, 72 areas meet that economic criterion. Proper management should favorably affect soil movement, wildlife habitat, and esthetics. Recreation use would be unaffected in most areas.

Keywords: chaparral control, multiple use, economic evaluation, cost estimation

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Keywords: chaparral control, multiple use, economic evaluation, cost estimation

PESTICIDE PRECAUTIONARY STATEMENT

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

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Effects of Pinyon-Juniper Removal on Natural Resource Products and Uses in Arizona

October 1974

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Abstract

Results from six treated and control watersheds, along with other results from the southwestern pinyon-juniper type, suggest that: (1) mechanical methods of pinyon-juniper removal are not likely to increase water yield; (2) removal of pinyon-juniper overstory by herbicides can increase water yield; (3) there has been no statistical verification of changes in flood peaks or water quality due to treatment; (4) herbage yields increase after virtually all pinyon-juniper treatments, but potential livestock carrying capacity varies greatly due to differences in plant composition; (5) the response by deer to these treatments is, on the average, neutral; (6) the more successful conversion projects just about break even from a benefit-cost standpoint under 1972 economic conditions.

Keywords: *Pinus edulis*, *Juniperus* spp., watersheds.

The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U. S. Department of Agriculture to the exclusion of others that may be suitable.

USDA Forest Service
Research Paper RM-128

October 1974

Effects of Pinyon-Juniper Removal on Natural Resource Products and Uses in Arizona

Warren P. Clary, Malchus B. Baker, Jr., Paul F. O'Connell, Thomas N. Johnsen, Jr., and Ralph E. Campbell

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University. Clary, Principal Plant Ecologist, Baker, Associate Hydrologist, and Campbell, Research Soil Scientist, are located at the Station's Research Work Unit at Flagstaff, in cooperation with Northern Arizona University; O'Connell, Principal Economist, is located at the Station's Research Work Unit at Tucson, in cooperation with the University of Arizona; Johnsen is Research Agronomist, Western Region, Agricultural Research Service, U.S. Department of Agriculture, located at Flagstaff.*

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Water shortages and threats of water shortages in central Arizona during the mid-1950's stimulated interest in watershed management. It was suggested that much of Arizona's nonagricultural land in the Salt and Verde watersheds should be managed primarily to improve overland water yields, while other uses would have a secondary consideration. Different forms of vegetation manipulation were recommended to achieve water yield increases (Barr 1956).These recommendations had particular significance because a large percentage of the State is in some type of Federal ownership or trusteeship. For instance, in the Salt and Verde watersheds, 55 percent of the pinyon-juniper[2] vegetation type is managed by the USDA-FS [U.S. Department of Agriculture, Forest Service] and 37 percent is within Indian reservations.

Since managers of Federal lands are committed to the multiple-use concept, any management policy which strongly affects the land must undergo serious examination before being implemented. Watershed studies were quickly set up by Federal agencies to study the impact of vegetation manipulation on watershed management (Kennedy 1959, Le Crone 1959, Reynolds 1959).

[2]*Common and botanical names of plants are listed at the end of this report.*

The intent of this Paper is to examine current results of water yield improvement tests in north-central Arizona in light of their impacts on multiple uses of the land. This examination includes water quantity and quality, overstory vegetation, understory vegetation, potential livestock carrying capacity, wildlife values, and recreation and esthetics. The changes in these values are considered in relation to management costs. Emphasis is placed on studies within the Beaver Creek watershed, Coconino National Forest, because considerable multiple use information has been developed there. Results from related studies are utilized as they apply.

The Beaver Creek Project was established in the late 1950's as part of the Arizona Watershed Program. The general objective of the Project was to evaluate land management measures designed to increase water yields. While water yield was to be given major consideration, changes in forage and timber production, wildlife populations, recreational value, and erosion and sediment movement were also to receive attention. Costs and benefits of the various treatments were to be studied so that all aspects of the Project could be evaluated (Brown 1971).

The Beaver Creek watershed is located along the Mogollon Rim on the Coconino National Forest. In 1957, six pilot watersheds were established in the pinyon-juniper type: three in the

Utah juniper subtype ranging from 126 to 362 acres, and three in the alligator juniper subtype ranging from 66 to 346 acres (fig. 1). On areas surounding these pilot watersheds, juniper was removed on several thousand acres as part of an action watershed-improvement program (H. Brown et al. 1974).

The treatments are being evaluated primarily by the USDA-FS with cooperation of Agriculture Research Service, Arizona Game and Fish Department, Arizona Land Department, Arizona Water Commission, Arizona Water Resources Committee, Colorado State University, Museum of Northern Arizona, Northern Arizona University, University of Arizona, and USDI Geological Survey. Additional background information can be found in H. Brown et al. (1974).

Research Background

Hydrology

Early estimates of potential water yield increases to be obtained by removal of pinyon-juniper overstory were 0.75 inch from bottom lands to 0.40 inch for slopes (Barr 1956). Later reports were less optimistic. Dortignac (1960) studied runoff efficiencies and infiltration

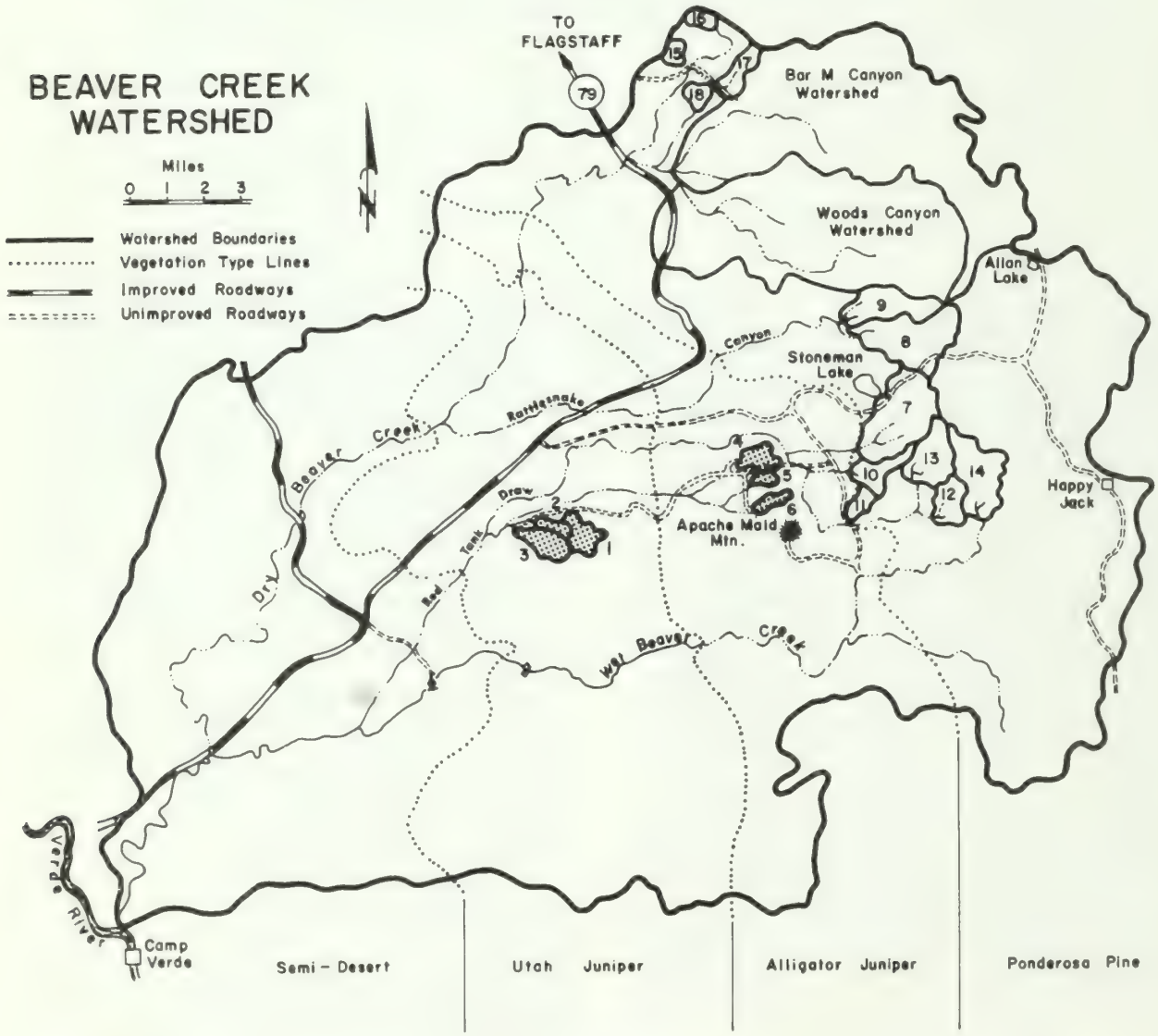

Figure 1.—The Beaver Creek watershed.

rates on pinyon-juniper watersheds, and reported that the possibilities for increasing overland flow were not promising. Skau (1964b) reported that although clearing of Utah juniper may increase the moisture available for forage production, it may have little effect on runoff. During his 2-year study there was little difference in soil moisture between cleared and natural areas, particularly during the winter when the majority of runoff occurs. All plots had unused soil moisture storage capacity.

If the small differential in soil moisture between cabled and natural areas were to be converted into overland flow, nearly one-half would be trapped by the pits created by cabling juniper trees. These pits were estimated to reduce annual flow by 0.09 to 0.27 inch (Skau 1961).

Gifford (1973) reported that only when the debris left from chaining was windrowed did runoff increase in southern Utah. This effect of windrowing was attributed to a combination of decreased infiltration rates caused by severe mechanical soil disturbance, and the retention storage effect which occurs when debris is present. Other work on various components of the hydrologic cycle has not provided strong evidence for or against the improvement of water yields by removal of pinyon-juniper stands (Collings 1966, Gifford and others 1970, Gifford and Tew 1969, Skau 1964a).

One of the earlier watershed tests of the effect of pinyon-juniper control was conducted on an area of sedimentary soils in eastern Arizona. Although pinyon-juniper vegetation was removed from 25 percent of the area by chaining, and brush and duff under ponderosa pine stands were removed by prescribed burning on 13 percent of the area, water yield did not change detectably (Collings and Myrick 1966).

Myrick (1971) attempted a different method of evaluating water yield response to pinyon-juniper removal. He used a "parameter model" to estimate water yields without treatment, and these estimates were compared with observed posttreatment water yields. Water yields were estimated to have increased for 2 years following treatment, then dropped below the expected untreated yields the third and fourth posttreatment years.

Considering all of the documented hydrologic results from the southwestern pinyon-juniper type, the possibility of increasing water yield through removal of the tree overstory does not appear very promising.

Erosion

It has been suggested that pinyon-juniper stands increase the rates of erosion and sediment movement by suppressing herbaceous understory vegetation (Arnold and Schroeder 1955). Dortignac (1956) found erosion in the Rio Grande Basin was closely related to the condition of the plant cover. Some studies in southern Utah, however, demonstrated no consistent decrease or increase in sediment yields following clearing of pinyon-juniper and seeding to grass (Gifford and others 1970). Other studies showed that both runoff and sediment yields could increase if the slash debris is windrowed following chaining (Gifford 1973).

Range

On the Fort Apache Indian Reservation, herbage yields were strongly depressed as the density of the pinyon-juniper stand increased. It was estimated 10 years would be required after tree removal for a site to reach maximum herbage yields when protected or winter grazed only. At the end of the 10-year period, grazing capacity should have increased threefold (Arnold and Schroeder 1955). Other speculations were that the average animal unit carrying capacity per section (640 acres) would increase from 7.1 to 22.8 in 10 years after pinyon-juniper control. Areas supporting very dense stands of pinyon-juniper would increase from 3.6 to 22.8 animal units per section after 20 years, assuming a potential herbage production of 650 pounds per acre, essentially all of which is palatable to livestock. The study areas were primarily on sedimentary soils (Barr 1956).

Aro (1971) evaluated pinyon-juniper conversion attempts made in four States. He found considerable variation in the success of removing the overstory and in improving forage yields. Forage yield increases varied from zero on some chained areas to 1,600 pounds per acre on some burned and reseeded areas.

The effect of pinyon-juniper control on livestock carrying capacity has not been precisely measured (or reported) in Arizona. Juniper control and reseeding efforts on sedimentary soils have been estimated to have increased livestock carrying capacity several times (Chilson 1964, Robinson 1965). Grazing capacity has increased three to four times on favorable sites (personal communication with Albert Thatcher, SCS, Phoenix).

Wildlife

The increase in forage plants after pinyon-juniper removal has a potential of benefiting game populations (Barr 1956). Initial results of

Arizona Game and Fish Department studies suggested, however, that controlling pinyon-juniper has had a largely neutral effect on deer populations, although some control procedures may be more beneficial than others (Jantzen 1966). Reynolds (1964) concluded that pinyon-juniper reduction could be done in a manner that maintained or improved habitat conditions for deer and elk.

Utilization and Value of Overstory Species

The potential economic products from the pinyon-juniper woodlands are quite varied. Fenceposts, firewood, lumber, veneer, particleboard, charcoal, pulp, extractive chemicals, pinyon nuts, and Christmas trees are some of the potential uses. Because of high per-unit costs woodland products have been harvested to only a limited degree, although recent energy shortages have greatly stimulated the harvest of firewood. Thus, pinyon-juniper control to date has not had significant economic impact on overstory products (Barger and Ffolliott 1972, and Barr 1956).

Methods of Overstory Removal

Large areas typically have been treated by cabling or chaining, while bulldozing or pushing has been used widely to remove individual trees. Hand clearing by axe and saw has been utilized in special situations. Broadcast burning has been reasonably successful where the pinyon-juniper stands were heavy and topography aided in fire control. Individual-tree burning and the use of herbicides have been utilized on a limited scale. The Nonstructural Range Improvements Handbook (USDA-FS 1970b) and the Guide to Improvement of Arizona Rangeland (Arizona Interagency Range Technical Sub-Committee 1973) provide excellent background information on selection of pinyon-juniper control techniques and range seeding methods.

The costs of initial tree removal have varied widely by method and situation (Aro 1971, Barger and Ffolliott 1972, Cotner 1963, Warskow 1967). Additional expenses are often involved, such as followup hand cutting of small trees missed by a chaining or cabling operation, slash burning, and seeding for forage species (Chilson 1964, Warskow 1967, Worley and Miller 1964). An optimum stand-selection procedure for juniper control has been developed by Jameson (1971). It takes into account the probable rate of overstory density increase, and rate of change of treatment costs for different treatments as the overstory changes.

A discussion of current juniper control costs can be found in a later section titled "Benefit-Cost Analysis."

Vegetation Type Description

Pinyon-Juniper of the Southwest

The pinyon-juniper type occupies over 60 million acres in western and southwestern United States (USDA-FS 1958). Fifty-one million acres occur in the Four-Corner States of Arizona, New Mexico, Colorado, and Utah (Dortignac 1960). The primary distribution of the type in these States corresponds to the distribution of pinyon (fig.2). Estimates of the acreage in Arizona vary from 12 million (Spencer 1966) to 14 million (Arnold and others 1964). The pinyon-juniper type covers over one-fourth of the Salt-Verde River Basin (Barr 1956) (fig.3).

This type is commonly referred to as a woodland rather than a forest because the trees are generally small and below sawtimber size. The climate of the pinyon-juniper type is rather severe for tree growth, characterized by low precipitation, hot summers, high wind, low relative humidity, very high evaporation rates, and much clear weather and intense sunlight. The annual precipitation for the type generally varies from 12 to 18 inches, with local areas up to 20 inches.

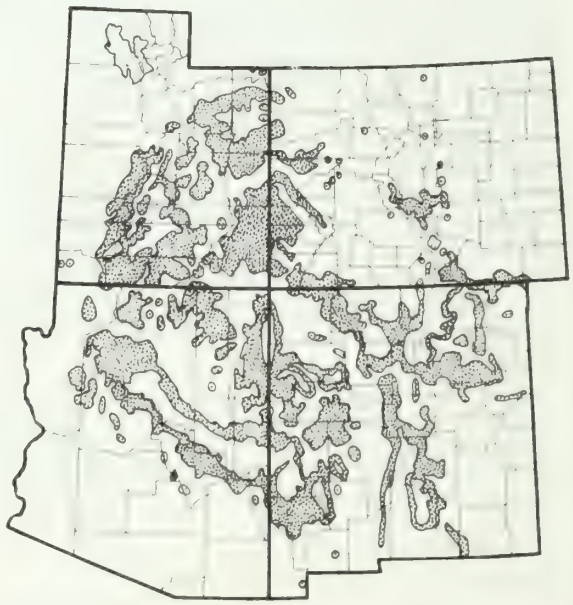

Figure 2.—Distribution of pinyon in the Four-Corner States (from Little 1971).

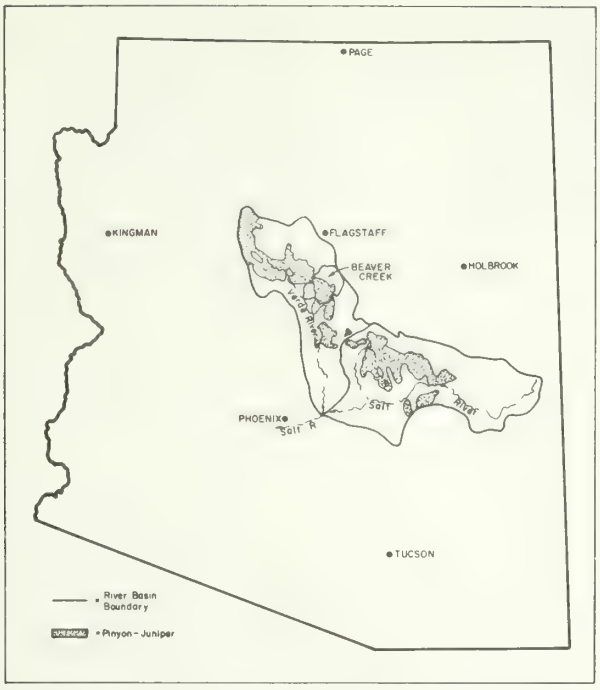

Figure 3.—Distribution of the pinyon-juniper type in the Salt and Verde River Basins (adapted from Spencer 1966).

In Arizona the pinyon-juniper woodland lies primarily between the elevations of 4,500 and 6,500 ft. It is flanked by ponderosa pine forests above and by desert shrub, chaparral, or semiarid grassland types below. Soils, which have developed from a wide variety of parent materials, vary from shallow and porous to moderately deep and very fine textured (Dortignac 1960, USDA-FS 1965, Williams and Anderson 1967).

The most consistent species in the woodland type is pinyon, although in Arizona one or several *Juniperus* species will usually dominate the stand. The three most common junipers in Arizona are Utah, one-seed, and alligator. The distribution of the juniper species and their related understory species appears to correspond to climate variations (Arnold and others 1964).

Pinyon-Juniper of the Beaver Creek Watershed

Physiography.—Sloping mesas and breaks, steep canyons, and valleys characterize the pinyon-juniper type on Beaver Creek. The bedrock underlying the area consists of igneous rocks of volcanic origin, and below that sedimentary rocks of Kaibab, Coconino, and Supai Formations.

The pilot watersheds in the Utah juniper subtype have a range in average elevation of 5,200 to 5,500 ft. The soils are developed from volcanic materials, primarily basalts. The predominant soil is Springerville very stony clay. The typical profile is 44 inches deep, with a clay texture throughout (Williams and Anderson 1967).

The pilot watersheds in the alligator juniper subtype have a range in average elevation of 6,200 to 6,400 ft. The soils have also developed from volcanic materials. In addition to the Springerville soils, the Gem soils are also important. The typical Gem profile is similar in depth to the Springerville, but is lighter textured and has a greater structural development (Williams and Anderson 1967).

Climate.—Annual precipitation ranges from 12 to 24 inches with an average of 18 inches in the Utah subtype, and 16 to 27 inches with an average of 20 inches in the alligator subtype (table 1). Respectively, 11 and 12 inches come during the months of October through April as snow and rain. Mean annual temperature in the Utah and alligator juniper subtypes has been 56°F and 50°F, respectively (table 1).

Vegetation.—The two pinyon-juniper subtypes on the Beaver Creek watershed represent the lower and upper woodland zones in the sub-Mogollon region of the Inland Southwest (Lowe 1961). In both subtypes pinyon is a minor component. Tree densities are given in tables 2 and 3.

Vegetation occurring under the pinyon-juniper overstory includes grasses, forbs, half-shrubs, and shrubs. The production of understory plants in the alligator subtype is greater compared to the Utah subtype, due largely to a lower overstory density. The range condition of the untreated areas is "very poor" in the Utah subtype and "poor" in the alligator subtype.

Wildlife.—The pinyon-juniper vegetation type on Beaver Creek supports a good variety of big game, carnivores, small game, rodents, and birds (Neff 1974) during all or a portion of the year. Rocky Mountain mule deer is the primary species sought by hunters, although a number of other game animals and game birds are hunted as well.

Water Yield Improvement Tests on the Beaver Creek Watershed

Treatments Applied

The woodland overstory was removed by

Table 1.--Average precipitation and temperatures in the two pinyon-juniper subtypes, Beaver Creek watershed

MONTH	PRECIPITATION[1]		TEMPERATURE[2]					
	Utah juniper subtype	Alligator juniper subtype	Utah juniper subtype			Alligator juniper subtype		
			Maximum	Minimum	Mean	Maximum	Minimum	Mean
	Inches		- - - - - - - - - °F - - - - - - - - - -					
October	1.02	1.06	72	43	58	66	38	52
November	1.64	2.00	60	33	46	54	29	41
December	2.10	2.55	52	26	39	48	23	36
January	1.47	1.85	51	24	38	46	21	34
February	1.30	1.33	54	27	41	48	23	35
March	1.90	2.07	58	31	44	51	25	38
April	1.40	1.42	66	38	52	60	31	45
May	.37	.53	76	45	61	68	38	53
June	.36	.39	86	54	70	80	46	63
July	1.53	1.58	91	62	76	85	54	70
August	2.70	2.68	87	60	73	81	53	67
September	2.40	2.79	82	54	68	76	47	61
Mean annual	18.19	20.23			56			50

[1]Based on 11 years of record.
[2]Based on 15 years of record.

Table 2.--Number of trees per acre, by species and diameter--Utah juniper subtype

Diameter (inches)	Utah juniper	Pinyon	All species
	- - *Stems per acre* - -		
0.1 - 4.9	40.8	13.3	54.1
5.0 - 8.9	42.8	.9	43.7
9.0 - 12.9	20.5	.8	21.3
13.0 - 16.9	8.6	1.0	9.6
17.0 - 20.9	3.9	0	3.9
21.0+	2.2	0	2.2
Total	118.8±26.4	16.0±14.4	134.8±29.1
	- - - *Percent* - - -		
	88	12	100

Table 3.--Number of trees per acre, by species and diameter--alligator juniper subtype

Diameter (Inches)	Alligator juniper	Utah juniper	Ponderosa pine	Pinyon	Gambel oak	All species
			Stems per acre			
0.1 - 4.9	92.9	11.3	6.8	3.8	0	114.8
5.0 - 8.9	10.8	3.1	1.2	0	.2	15.3
9.0 - 12.9	2.0	.2	.8	.1	.2	3.3
13.0+	2.1	.2	.3	0	0	2.6
Total	107.8±20.7	14.8±7.5	9.1±2.2	3.9±3.1	0.4±0.3	136.0±22.1
			Percent			
	79	11	7	3	T	100

three different techniques—cabling, herbicide, and felling—in an attempt to increase water yield.

The cabling treatment, applied to watershed 1 (Utah subtype) in 1963, was similar to that extensively applied in the Southwest for range improvement. The larger trees were uprooted by a heavy steel cable pulled between two bulldozers (fig. 4); small trees missed by the cable were hand chopped, slash was burned, and the area was seeded with a mixture of forage species (Brown 1965).

The herbicide treatment of watershed 3 (Utah subtype) in 1968 consisted primarily of a helicopter application of 2½ pounds of picloram and 5 pounds of 2,4-D per acre (fig.5). The intent was threefold; (1) to reduce transpiration losses by killing trees, (2) to reduce evaporation losses by leaving the dead trees standing to reduce windspeed and insolation, and (3) to avoid the

Figure 4.—Uprooting trees by pulling a cable between two tractors on watershed 1.

Figure 5.—Applying herbicide by helicopter to kill trees on watershed 3.

Figure 6.—Felling alligator juniper on watershed 6.

problem of overland water flow being trapped in soil pits created when trees are uprooted (Brown 1971). No forage species were seeded. One year previously, 2,4-D and 2,4,5,-T had been applied to watershed 3 to desiccate the tree foliage preparatory to a burning treatment. Because the burning attempt was unsuccessful, it was decided to kill the trees in place by chemicals rather than by fire.

The felling treatment on watershed 6 (alligator subtype) was conducted in 1965. The trees were cut by powersaws (fig. 6) and left in place, thus avoiding pitting and other types of soil disturbance. Stumps of alligator juniper were treated with polychlorinated benzoic acid to reduce sprouting; shrub live oak was treated initially with fenuron and later with picloram; Gambel oak sprouts were treated with a dormant-season basal spray of 2,4,5-T (Brown 1971). No forage species were seeded.

The mechanical treatments on watersheds 1 and 6 resulted in nearly 100 percent overstory removal. Approximately 83 percent of the overstory stand on watershed 3 was killed by the herbicide application,[3] with vigor of many of the remaining trees severely reduced. A higher survival rate among smaller trees suggested that they benefited from the protection of the larger trees.

[3]*Larson, Frederic R. Posttreatment inventory of Utah juniper watershed No. 3 on Beaver Creek. Unpubl. Off. Rep., 1970. Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

Measurement Techniques

New techniques in stream gaging have been utilized to accurately measure the broad range of debris-laden discharges carried by the streams. A concrete trapezoidal flume was designed for use on the small watersheds. The design was a modification of a Washington State College flume, adapted to Beaver Creek conditions (Robinson 1961). The watersheds are organized into an experimental design to provide a basis for statistical evaluation of changes in streamflow. Watersheds within each vegetation type are paired, with some scheduled for treatment and others retained untreated as statistical controls. Following pretreatment calibration, one watershed in each pair is treated. These methods are described by Kovner (1956), Kovner and Evans (1954), and Wilm (1943.)

The sediment data were obtained by means of the catchment basins and splitting devices illustrated and described by Brown and others (1970). In addition to measurements of total sediment, suspended sediment concentration has been sampled on all watersheds.

Chemical water quality samples have been collected under different conditions. Most samples were of runoff from melting snowpack and were taken from the flume, either dipped or with a DH-48 sampler. A few were collected from the sediment storage tanks below splitter installations. Samples were stored in glass containers and sent to a USGS (U.S. Geological Survey) laboratory. Analysis included pH, electrical conductivity, total dissolved solids, hardness, silica as SiO_2, calcium, magnesium, sodium, potassium, bicarbonate, carbonate, sulfate, chloride, and fluoride. Iron, manganese, boron, nitrate, and phosphate were also included in the analysis of some samples.

The range inventories primarily involved plot measurements of plant production and utilization, and transect measurements of condition and trend. Measurements were made periodically at 10 locations within each watershed. On five 9.6-ft² plots at each location, herbage production was determined for each species by weight estimate and checked by clipping and weighing (Pechanec and Pickford 1937a). Forage utilization was determined by the ocular-estimate-by-plot method (Pechanec and Pickford 1937b). Range condition, including ground cover and plant frequency, was determined by the method of Parker (1954).

Big-game populations and use have been measured primarily by the Arizona Game and Fish Department. Changes in occupancy of the watersheds by deer and elk are estimated from counts of fecal droppings on plots superimposed on the tree overstory inventory points. Forage preferences of deer are determined by observing the plants eaten by tame deer under different treatment conditions. Production of preferred wildlife forage is determined by combining species yields and preference information.

Streamflow Response

Responses of annual and winter streamflow to vegetation treatments on the pinyon-juniper watersheds are presented in table 4. Mean annual streamflow for the untreated condition is based on variable periods of record for the given watersheds, and has been adjusted by covariance to minimize variation due to climate and other factors not associated with treatment. Responses for individual years following treatment are determined by subtracting the flow predicted by covariance from the actual. Average treatment responses are expressed quantitatively in inches and as a percent of the pretreatment mean. Probability levels at which the current responses are statistically significant are indicated.

The only significant response in annual streamflow is from the herbicide treatment on watershed 3. This response increase averages 0.45 inch or 65 percent over a 4-year period, and is statistically significant at the 2.5 percent level. The streamflow response from the felling treatment on watershed 6 was 0.38 inch or 14 percent over a 7-year period, which is not significant at the 10 percent level. (Although a

Table 4.--Summary of treatment effects on annual and winter streamflow for three Beaver Creek pinyon-juniper watersheds, by subtypes

Watershed, by subtype, treatment, year treatment completed, and streamflow recorded	Mean streamflow[1]	Difference between actual and predicted streamflow by years following treatment									Mean difference[2]		Level of significance[3]
		1st	2d	3d	4th	5th	6th	7th	8th	9th			
	Inches	*Inches*									*Inches*	*Percent*	
UTAH JUNIPER SUBTYPE:													
Watershed 1-- Cabled, slash burned 1963													
Annual streamflow	0.77	-0.36	-0.04	0.28	-0.08	0.18	0.12	([4])	0.03	0.01	0.02	3	NS
Winter streamflow	.62	.07	-.11	.22	-.04	.13	.06	.02	-.02	-.04	.03	5	NS
Watershed 3-- Herbicide, no removal or burning 1968													
Annual streamflow	.69	.39	1.19	.04	.17						.45	65	0.025
Winter streamflow	.52	.31	.85	.03	.11						.32	62	.025
ALLIGATOR JUNIPER SUBTYPE:													
Watershed 6-- Felled, no burning, regrowth restricted 1965													
Annual streamflow	2.63	.53	.90	-.12	.17	.75	.25	.21			.38	14	NS
Winter streamflow	2.49	.46	.90	-.09	.17	.29	.26	.16			.31	12	NS

[1]Adjusted by covariance for years 1958-72 for watersheds 1 and 3; 1961-72 for watershed 6.
[2]Adjusted by covariance.
[3]NS indicates nonsignificance at the 0.10 level.
[4]Due to quality of data, response for water year 1970 was not included in covariance analysis. Streamflow response for 1970 was probably between +0.71 and +0.90 inch.

treatment response for watershed 6 was indicated, the streamflow calibration was not sufficiently precise to detect a 14 percent change in water yield.)

Watershed 1, where overstory was removed by cabling, has had a 9-year evaluation period. The seventh-year response was not included in the covariance analysis because the major portion of this annual runoff came during the storm on September 5, 1970. During this storm, the flume was overtopped and the stream-gage rating was affected by debris blocking the flume. The estimated range of annual response during this year is from 0.7 to 0.9 inch, nearly four times larger than the next highest response (table 4). Because of the questionable quality of data and because most of the runoff came during such an extreme event (estimated to have a recurrence interval of 100 to 150 years), Water Year 1970 was left out of the calculated mean response. The remaining years of data for watershed 1 show no significant change in streamflow due to treatment.

The winter streamflow response (table 4) is similar to the annual streamflow response, and also shows that only the herbicide treatment on watershed 3 significantly increased water yield.

The explanations for the lack of change in water yields following the cabling of watershed 1 are largely speculative. A combination of water entrapment by soil pits (Skau 1961), heavy growth of herbaceous vegetation (mainly forbs and half-shrubs), and greater evaporation losses probably compensated for the reduction in transpiration of the overstory. The primary reasons for the striking difference in response between the herbicide and the cabling treatments have not been experimentally determined. There is little doubt, however, that the lack of soil pitting and the reduction of solar radiation and windspeed by the standing dead trees play a role in the water yield increase from watershed 3.

Soils on watershed 3 deeper than 12 inches did not dry to the permanent wilting point from the first winter following treatment until the late summer of 1972, about 4 years. In untreated areas, the soils were dry much of each year. Similar responses have been observed with small plot studies of herbicidal vegetation control elsewhere (Johnsen 1970). The lack of rapid soil moisture loss on watershed 3 may be due to the replacement of deep-rooted trees with generally shallow-rooted annual plants which would not deplete moisture below the surface foot of soil. The dryness of the soil during the fourth summer after treatment may be due to either an increase in deeper rooted plants or to the very dry preceding winter. When the subsurface soil remains moist, less precipitation is needed to wet the soil sufficiently for runoff to occur.

The mean annual runoff from the untreated alligator juniper watersheds was 4.3±1.0 inches with a runoff efficiency of 21 percent, compared to 0.8±0.3 inch from the untreated Utah juniper watershed for a runoff efficiency of 4 percent. The portion of the total runoff occurring in the period of October through April was 96 percent and 74 percent, respectively (figs. 7 and 8). Streamflow efficiency for the seasonal period October-April was 34 and 6 percent, and for May-September was 2 and 3 percent for the alligator and Utah juniper, respectively.

Even though water yield efficiency is higher on the alligator juniper than on the Utah juniper watersheds, the felling treatment on watershed 6 (alligator juniper) has not resulted in a significant streamflow response. The characteristically low overstory density of the alligator juniper subtype on Beaver Creek may provide little opportunity to create a measurable water yield increase with any type of vegetative manipulation. Areas of alligator juniper with stands approaching the densities of the Utah juniper watersheds may have the potential, however, to give a measurable water yield increase upon tree removal.

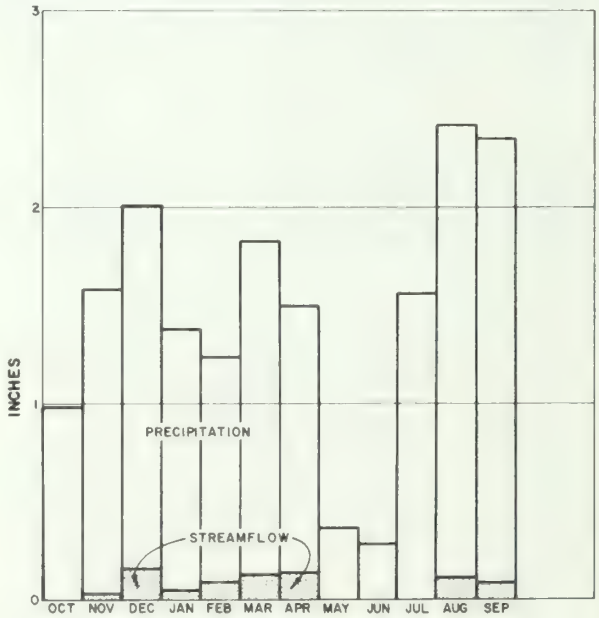

Figure 7.—Average monthly streamflow and precipitation in the Utah juniper subtype on Beaver Creek. Streamflow data are from watershed 2; precipitation data are from three gages on watersheds 2 and 3.

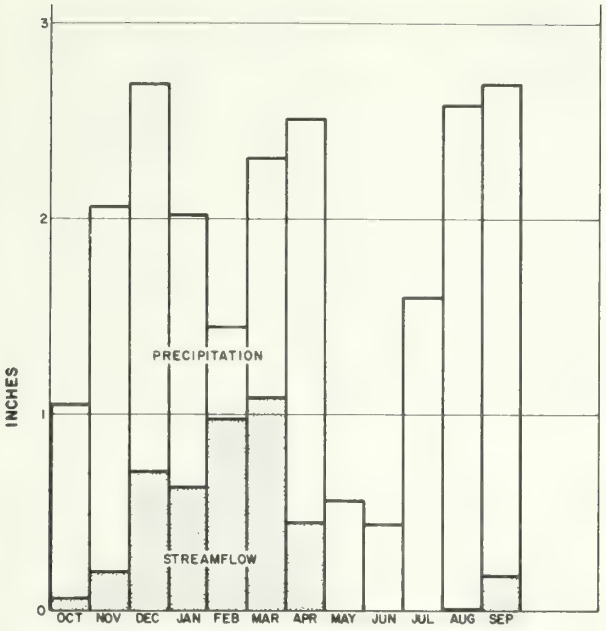

Figure 8.—Average monthly streamflow and precipitation in the alligator juniper subtype on Beaver Creek. Streamflow data are from watersheds 4 and 5; precipitation data are from three gages on watersheds 4, 5, and 6.

Attempts to predict streamflow from the Beaver Creek pinyon-juniper watersheds using simple regression models have been only moderately successful. Since two treatments produced no detectable water yield increase, there was little basis for describing the effect of overstory removal on water yield. Precipitation was the only variable significantly contributing to the predictions of streamflow. Winter precipitation was a better predictor than annual precipitation, and was as good as using winter and summer precipitation as independent predictors. The equations are:

Utah juniper watersheds—
  Annual runoff $Y = 0.25X - 2.00$; $r = 0.70$
  Winter runoff $Y = 0.28X - 2.50$; $r = 0.77$
Alligator juniper watersheds—
  Annual runoff $Y = 0.94X - 8.08$; $r = 0.90$
  Winter runoff $Y = 0.96X - 8.50$; $r = 0.89$
where
Y = inches of runoff, and
X = inches of winter precipitation.

Winter precipitation is a fairly good predictor of annual runoff because 74 percent of the annual runoff from the Utah juniper subtype and about 96 percent from the alligator juniper subtype occur during the winter period.

Progress in modeling water yields from other southwestern pinyon-juniper watersheds has been reported by the U.S. Geological Survey (Myrick 1971). Concerning the other water yield models available, the Stanford Watershed Model (Crawford and Linsley 1966) is not suited for application on small watersheds. The USDA model (Holtan and Lopez 1971) is not applicable in this area because it does not account for snowmelt runoff. Water Yield 1 (USDA-FS 1972) may be applicable to this area, but has not been available for testing. Leaf and Brink's (1973) hydrologic model will be tested once it has been modified to function in areas with shallow or intermittent snowpacks. Rogers' (1973) model has not been tested in the pinyon-juniper type pending more thorough evaluations of results from the ponderosa pine type. While testing of the BURP Model (USDA-FS 1968) on Beaver Creek has been considered, all model evaluation has been delayed until completion of an overall determination of models needed to provide information for management of the southwest forest ecosystems.

Flood Peak Response

A major storm which struck Beaver Creek in September 1970 (Baker and others 1971) provided an opportunity to assess the effect of the pinyon-juniper treatments on flood peaks. Total precipitation for this 24-hour storm period ranged from 3.9 to 4.9 inches on the six pinyon-juniper watersheds. Peak runoff discharges ranged from 400 to 700 $ft^3/s/mi^2$ (cubic feet per second per square mile) and total runoff from 0.76 to 2.00 inches. Treatment responses (table 5) were estimated graphically, based on the relationship between peak discharge and 60-minute precipitation intensity (fig. 9). These estimates are based on the assumption that the change in runoff response of treated watersheds from the untreated relationship represents the response to vegetation manipulation. These estimates are not subject to statistical verification, however. Table 5 also contains the estimated recurrence intervals for the observed peak discharges.

The largest response was from the cabling treatment on watershed 1. The increase in peak discharge due to treatment was estimated to be 250 $ft^3/s/mi^2$, or 60 percent.

Sediment Yield Response

Mean annual sediment yields from the untreated pinyon-juniper watersheds sampled on Beaver Creek (13 station years) have varied from 0.01 to 0.27 ton per acre, with an average of 0.10 ton per acre over a 9-year period of record.

Table 5.--Summary of treatment effects on flood peaks for the September 1970 storm on the pinyon-juniper watersheds

Watershed, by subtype, treatment, and year treatment completed	Flood peak			Estimated recurrence interval[1]	Since treatment
	Estimated for untreated conditions	Actual	Estimated difference due to treatment		
	$Ft^3/s/mi^2$			Years	
UTAH JUNIPER SUBTYPE:					
Watershed 1-- Cabled, slash burned 1963	450	700	250	100-150	7
Watershed 3-- Herbicide, no removal or burning 1968	400	500	100	50	2
ALLIGATOR JUNIPER SUBTYPE:					
Watershed 6-- Felled, no burning, regrowth restricted 1965	550	600	50	40	5

[1]As determined by the USGS, Tucson, Arizona, using regionalized peak discharge from the Beaver Creek watersheds.

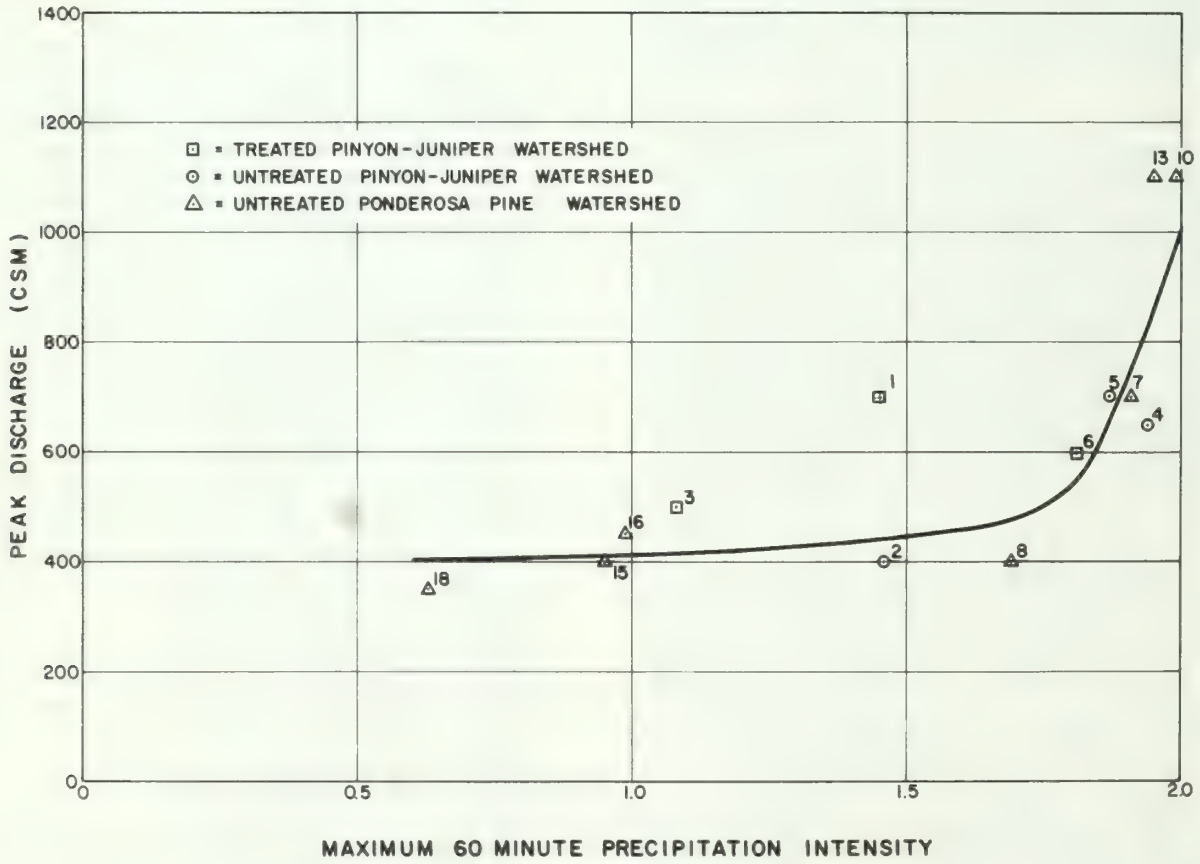

Figure 9.–Relationship of peak discharge to precipitation intensity on Beaver Creek for the 1970 Labor Day storm.

Mean winter sediment yields from untreated watersheds have ranged from a trace (less than 0.005 ton per acre) to 0.27 ton per acre, with an average of 0.07 ton per acre; summer yields have ranged from 0 to 0.27 ton per acre, with an average of 0.03 ton per acre. These mean values indicate that over 50 percent of the sediment in the pinyon-juniper type is generated during the winter season. This seasonal relationship is even more striking when one considers that eight of nine summer seasons had sediment yields of 0.005 ton or less per acre. The remaining summer (1970) had a sediment yield of 0.27 ton per acre from untreated watershed 4 as the result of a storm which had an estimated recurrence interval of 100 years.[4]

Mean annual sediment yields from treated pinyon-juniper watersheds on Beaver Creek have varied from a trace to 1.1 tons per acre on a cabled watershed, and from a trace to 0.08 ton per acre on a herbicide-treated watershed. Because of the short period of record (13 station years) and confounding due to treatment intensity, storm frequency, and climatic variation, a mean cannot realistically be calculated to generalize the treated condition in the pinyon-juniper type on Beaver Creek.

The largest sediment yield of 1.1 tons per acre was produced on a cabled watershed during the September 1970 storm, which produced a peak discharge of 800 $ft^3/s/mi^2$ with an estimated recurrence interval of 100 to 150 years. This watershed received a maximum 30-minute precipitation intensity of 2.17 inches per hour and a total storm precipitation of 4.06 inches. The only peak discharge in the pinyon-juniper type on Beaver Creek which exceeded this amount during the period of record was on the same watershed in 1964, 1 year after its cabling treatment. The discharge of 1,000 $ft^3/s/mi^2$ produced a sediment yield of 0.33 ton per acre. The storm producing this discharge occurred on August 3, 1964, and had a total precipitation of 1.59 inches over a 45-minute period, with a maximum 30-minute intensity of 3.14 inches per hour. Apparently the greater total rainfall in 1970 was a factor in producing over three times more sediment than the storm event in 1964.

Based on records obtained during the past 9 years on Beaver Creek, and from knowledge of sediment losses resulting from various treatment intensities and storm frequencies, it appears that sediment yields of 1 to 2 tons per acre are approaching the maximum sediment loss potential for watersheds with similar physical characteristics and climatic regimes in the pinyon-juniper type. We also conclude that there appears to be no meaningful change in sediment yield after either cabling or applying herbicide in the pinyon-juniper type.

We have attempted to predict sediment yield from Beaver Creek pinyon-juniper watersheds using simple regression models. Runoff was the only variable which contributed significantly to prediction of sediment yields. Seasonal runoff was found to be a better predictor of seasonal sediment yields than annual runoff was for predicting annual sediment yields. The equations are:

Winter sediment—
$Y = 0.02X - 0.01$; $r = 0.70$
Summer sediment—
$Y = 0.13X$; $r = 0.99$
where
Y = tons per acre of sediment, and
X = inches of seasonal runoff.

Since runoff was the primary factor influencing sediment yields, and overstory removal had little effect on runoff from the pinyon-juniper watersheds, the above equations are assumed to apply equally well to treated and untreated areas.

Water Quality Response

Seven primary water quality samples have been analyzed from pinyon-juniper watershed runoff. Samples taken on watersheds 1 and 3 on April 6, 1964, (table 6) represent the entire spring runoff, which was caught by the sample splitters and stored in sediment tanks. The TDS (total dissolved solids) content of the water from the treated watershed was 148 mg/l or 2.4 times as great as from the untreated watershed (62 mg/l). The increases in amounts of Ca, Mg, Na, K, and HCO_3 were proportionally different. Water from watershed 1 contained approximately 3.5 times as much sulfate and chloride as did watershed 3, but the silica and nitrate contents were not greatly different.

On the basis of the March 1964 runoff record and the analyses reported here, watershed 1 produced 0.1 inch of runoff per acre and lost 3.26 pounds of dissolved salts per acre. In contrast, for the same series of events, watershed 3 produced 0.003 inch of runoff and lost 0.04 pound of dissolved salts per acre.

Runoff from watersheds 2 and 3 were both dip-sampled at the flumes in January 1969. Watershed 3 had been treated with herbicide in 1968, whereas watershed 2 remained untreated. The TDS in the runoff from watershed 3 was 117 mg/l as compared to 104 mg/l from untreated watershed 2 (table 6).

[4]*Based on estimates made by USGS, Tucson, Arizona.*

Table 6.--Analyses of water samples from the pinyon-juniper subtypes, Beaver Creek watershed

Watershed, by subtype, and date sample taken	pH	Conductivity	TDS	SiO_2	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	Fe	Mn	F	B	CO_3	Hardness
		$EC \times 10^6$								Mg/ℓ								$MgCaCO_3$/ℓ
UTAH JUNIPER SUBTYPE:																		
Watershed 1--																		
April 6, 1964	7.3	251	148	9.6	33	8.9	4.2	3.6	120	21	1.1	0.4	0.22	--	0.4	--	0	119
Watershed 2--																		
January 26, 1969	7.0	163	104	13	22	[1]4.1	[1]4.5	[1]3.5	96	7	2.5	--	0	--	.2	--	0	72
Watershed 3--																		
April 6, 1964	7.1	99	62	8.3	13	3.3	2.2	1.5	51	6.2	.9	.7	.32	--	.3	.03	0	46
January 26, 1969	8.0	182	117	15	25	[1]5.2	[1]4.0	[1]3.0	98	12	4.5	--	0	--	.2	--	0	84
September 19, 1970	8.3	266	161	15	38	9.6	4.7	3.4	175	.5	3.2	0	.01	0.02	.1	--	0	130
Mean	7.5	192	118	12	26	6.2	3.7	2.8	108	9.3	2.4	.4	.18	.02	.2	.03	0	90
ALLIGATOR JUNIPER SUBTYPE:																		
Watershed 5--																		
March 8, 1966	6.7	74	54	15	7.3	2.4	3.7	1.8	34	5.8	.4	.2	.99	--	.1	0	0	28
Watershed 6--																		
March 8, 1966	6.5	89	68	18	9.7	3.4	3.0	2.7	41	9.1	1.2	.4	.35	--	.2	0	0	38
Mean	6.6	82	61	16	8.5	2.9	3.4	2.2	38	7.6	.8	.3	.67	--	.2	0	0	33

[1]Estimated.

Only two water quality analyses were made in connection with the alligator juniper felling on watershed 6 in 1965. Water samples were dipped from the flumes of watershed 6 and control watershed 5 in March 1966. The runoff represented both rain and snowmelt. The water from the treated watershed contained 68 mg/l TDS as compared to 54 mg/l TDS from the control. The individual ion concentrations varied between the two samples in about the same proportion as the TDS except for chloride, which was three times higher on watershed 6.

Water produced from the juniper watersheds generally exceeded minimum quality standards (National Technical Advisory Committee 1968) for irrigation, public water supply, and for aquatic life. However, the iron content on some of the samples exceeded the recommended standard for aquatic life and for drinking water. All samples had extremely low SAR (sodium absorption ratio) values. All electrical conductivity values (μ mho/cm) were low (less than 100) on the alligator juniper watersheds, while two of three posttreatment samples from the Utah juniper watersheds showed a slight deterioration in respect to irrigation. The latter still exceeds drinking water and aquatic life standards, and its use would be unrestricted for irrigation.

Water from the Utah juniper watersheds was moderately hard and from the alligator juniper watersheds it was soft, based on the classification of Durfor and Becher (1964, p. 27). Suspended sediment was determined on samples taken concurrently with water quality samples. Correlation analysis showed no consistent relation between suspended sediment and TDS.

The total dissolved solids in the runoff water average 118 mg/l from the Utah juniper subtype and 61 mg/l from the alligator juniper subtype, compared with 46 mg/l from ponderosa pine watersheds (H. Brown et al. 1974). These concentrations do not reflect greater total dissolved material from the Utah juniper watersheds, however. Winter runoff is least from the Utah juniper, and this lower volume of runoff overshadows the concentration of dissolved solids when calculating the total dissolved solids leaving the area.

In addition to the above analyses, 24 paired runoff samples collected for herbicide residue determinations were also tested for nitrate content. These dip samples, taken at the flumes of Utah juniper watersheds 2 and 3 from 1969 through 1972, showed no evidence of increased nitrate contamination of surface runoff water. Usually, nitrate concentration was below the lowest reliable detection limit of the methods used, about 0.5 mg/l. The greatest amount detected was 36 mg/l in water from the untreated watershed 2, an amount approaching the limit set for potable water. Much of the nitrate which would be expected to be released from the dead trees on watershed 3 may have been used on site by the abundant annual vegetation which appeared following treatment.

Information on herbicide residues can be found in a later section titled "Efficacy of Herbicide Applications."

Vegetation Response and Changes in Potential Livestock Carrying Capacity

The production of understory plants in the untreated alligator juniper subtype averaged 518 pounds per acre, about 2.7 times the production of the Utah juniper subtype (194 pounds per acre) largely as a result of differences in tree density. The original tree basal area and tree crown cover for the pinyon-juniper watersheds (see fig. 1) were:

Watersheds by subtype	Tree basal area (Ft^2/acre)	Crown cover (Percent)
Utah juniper:		
1	(No data)	28±2
2	57±8	30±2
3	53±7	28±2
Average	55±5	29±1
Alligator juniper:		
4	17±2	12±1
5	19±3	14±1
6	24±3	13±2
Average	20±2	13±1

Cabling, hand chopping remaining trees, and burning of slash effectively removed the overstory from watershed 1. Because of this thorough overstory removal, the area is expected to remain dominated by herbaceous vegetation for a number of years. The estimated increase in annual production of grasses, forbs, and half-shrubs on watershed 1 is approximately 700 pounds per acre or 614 percent. The largest increases were in perennial grasses and in forbs and half-shrubs (table 7). The success of the seeded forage species was quite erratic (fig. 10). The understory species which are defined as livestock forage (USDA-FS 1970a) on watershed 1 increased an estimated 180 pounds per acre or nearly 300 percent as a result of treatment.

A commonly used conservative conversion of available forage to livestock carrying capacity is 1,000 pounds of forage per AUM (annimal unit month). However, if we assume the range is grazed seasonally rather than yearlong, 750 pounds of forage per AUM is more realistic because shattering loss will be much less during the grazing period. At 40 percent utilization, the livestock carrying capacity would then be about 0.02 AUM/acre before treatment and 0.13 AUM/acre after treatment.

The actual increase in forage plants, and therefore in relative carrying capacity, can vary from near zero after 10 years (Clary 1971) to perhaps 1,000 pounds per acre or more in favorable years if sufficient effort is put into the reseeding attempt. Results of seeding trials in the Utah juniper subtype on Beaver Creek indicate side-oats grama, western wheatgrass, pubescent wheatgrass, and yellow sweetclover are well adapted and high yielding (personal communication with Fred Lavin, ARS, Flagstaff). Side-oats grama and pubescent wheatgrass planted in 1966 yielded 1,431 and 2,315 pounds per acre, respectively, in 1969, and 1,109 and 809 pounds per acre on 1970. Western wheatgrass yielded 1,012 and 1,353 pounds during the same years. A large potential yield of

Table 7.--Summary of treatment effects on herbaceous and shrubby plant production[1] from the two pinyon-juniper subtypes, Beaver Creek watershed

Watershed, by subtype, treatment, and year treatment completed	Plant group	Production for untreated conditions	Difference between actual and predicted production by years following treatment								Level of significance[2]
			1st	2d	3d	4th	5th	6th	7th	Average	
		Pounds per acre									
UTAH JUNIPER SUBTYPE:											
Watershed 1--	Perennial grasses	29	111	130	200	--	81	162	--	137	0.05
Cabled, slash burned 1963	Annual grasses	3	29	10	0	--	28	3	--	14	NS
	Forbs and half-shrubs	73	1,032	260	339	--	231	849	--	542	0.05
	Shrubs	9	1	-2	2	--	4	32	--	7	NS
Watershed 3--	Perennial grasses	12	19	21	47	55	--	--	--	36	0.10
Herbicide, no removal	Annual grasses	6	145	83	15	48	--	--	--	73	0.10
or burning 1968	Forbs and half-shrubs	74	8	535	468	515	--	--	--	382	0.05
	Shrubs	17	-5	-21	-18	-20	--	--	--	-16	NS
ALLIGATOR JUNIPER SUBTYPE:											
Watershed 6--	Perennial grasses	282	73	126	49	78	16	362	84	113	0.05
Felled, no burning,	Annual grasses	0	0	0	0	0	0	0	0	0	NS
regrowth restricted 1965	Forbs and half-shrubs	347	104	241	55	34	6	219	281	134	0.15
	Shrubs	0	0	0	0	0	0	0	0	0	NS

[1]All values, in pounds per acre, were obtained as follows: (1) the pretreatment ratio was determined between the treated watershed and its control watershed; (2) this ratio was applied to the posttreatment control mean to obtain an estimate of posttreatment production for untreated conditions; (3) the ratio was applied to individual year data of the control and the result subtracted from the observed production to provide an estimate of annual change. The significance of treatment response was determined by covariance.

[2]NS indicates nonsignificance at the 0.15 level.

Figure 10.—Lovegrass was successfully established in some areas (a) while other areas (b) were dominated by broom snakeweed and annual goldeneye.

forage is indicated from seeding Utah juniper ranges in the Beaver Creek area. Native forage plants can also increase moderately within 10 years, but only if a basic forage component is present at the time of tree removal (Clary 1971).

The herbicide treatment of watershed 3 also resulted in significant increases in production of understory plants (table 7), but the pattern differed from cabled areas, which were quickly dominated by forbs and half-shrubs if perennial grasses were not present. The first year following the herbicide application the watershed was a waving field of red sprangletop, an annual grass (fig. 11). This species made 58 percent of the understory production, causing a significant increase in total yields 1 year after treatment. Total forb and half-shrub production was similar to the pretreatment period, but broom snakeweed, rough menodora, and sulfur eriogonum (half-shrubs) were largely replaced by spurge and common sunflower (annuals). The abundance of red sprangletop was reduced by one-half the second year, but the forb-half-shrub component increased 535 pounds per acre. Goosefoot, Russianthistle, prickly lettuce, and conyza were important in the second-year composition. Prickly lettuce was the most important single species on watershed 3 for the next several years. The estimated increase in understory yield following the herbicide treatment was 576 pounds per acre, or 528 percent. This figure does not include the first posttreatment year, which was eliminated due to possible carryover herbicide effects.

The production of forage plants on watershed 3 before treatment was almost nil. Since few native forage plants were present and no artificial seeding was done, production of desirable forage has changed little except for small local areas. It is estimated that actual forage production has increased about 65 pounds per acre. The few forage plants existing on the area have very high vigor, however, suggesting that if this treatment were applied to an area with a good residual stand of perennial grasses and other forage species, the livestock carrying capacity would be much improved.

The felling treatment on watershed 6 effectively removed the tree overstory. However, the followup control of alligator juniper and Gambel oak regrowth (sprouts), and the original control of shrub live oak by chemicals was less successful. In 1969, 4 years following treatment, 24 of 130 circular plots with 8.2 ft radius were stocked with woody plants.[5] Without additional followup treatment, this watershed will again in a few years have an aspect of a lightly stocked woodland.

The felling of alligator juniper, rather than bulldozing, resulted in minimum disturbance to the native grass stand. No forage species were seeded. The average increase in total plant production on this felled watershed was 242 pounds per acre, or 38 percent. The yields of forage plants increased 45 percent, or about 130

[5]*Larson, Frederic R. Reproduction survey of clearcut alligator juniper Watershed No. 6 on Beaver Creek. Unpubl. Off. Rep., 1969. Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

Figure 11.—Comparison of understory plants in 1968: (a) red sprangletop on watershed 3; (b) half-shrubs on an adjacent area of watershed 2.

pounds per acre (Clary 1974)—a potential grazing capacity increase of 0.07 AUM/ acre.

Several relationships have been developed for estimating the effect of pinyon-juniper overstory on understory plant production in Arizona (Arnold and Schroeder 1955, Arnold and others 1964, Clary 1971, Jameson 1967). Jameson (1971) developed perhaps the most generally useful relationships, involving different grass growth-forms and soils. Other relationships of potential herbage yields to soil characteristics and topography are also described (Clary 1964).

Because the soils and topography within the individual vegetation subtypes on Beaver Creek are rather uniform, they were not utilized to predict herbage yields in the present simple regression models. These regressions, which use watershed-years as a data base, do not provide precise predictions of herbage yields, but they do give an indication of what can be expected.

Tree basal area and summer precipitation are used to predict herbage yields (grasses, forbs, and half-shrubs) for the two subtypes. The regressions are:

Utah juniper watersheds—

$Y = 346.4 - 129.4X_1 + 28.3X_3$; $r = 0.85$

Alligator juniper wtersheds—

$Y = 593.3 - 357.0X_1 + 75.4X_2$; $r = 0.72$

Alligator juniper watersheds—

X_1 = log (tree basal area +2)

X_2 = June to August precipitation

$X_3 = X_2/X_1$

These equations illustrate measured differences in plant response between the subtypes. When there is no overstory, the herbaceous plant yields are similar (fig. 12). However, an overstory depresses herbage yields much more in the Utah juniper subtype than in the alligator juniper subtype. Likewise, in the Utah juniper subtype the herbaceous plants under a tree stand are less responsive to differences in precipitation than are herbaceous plants in the alligator juniper subtype. Some of the reasons for this difference in plant response, primarily soil related, are discussed by Jameson (1971) and Jameson and Dodd (1969).

The above regressions illustrate what can be expected for total herbage yields. The actual animal carrying capacity of an area depends very highly upon plant composition. Therefore, forage plant composition must be determined before regression estimates can be used to estimate potential animal carrying capacity.

Habitat Change and Wildlife Response

Deer numbers have changed considerably in the pinyon-juniper on Beaver Creek (Neff 1972a, 1972b). Mean annual deer densities in the Utah juniper subtype have decreased from about 36 per section (640 acres) in 1960 to between 4 and 5 per section since 1962. This reduction was part of a regional decline in deer populations (Wallmo 1964). In the alligator juniper subtype deer numbers decreased from approximately 20 deer per section in 1960 to 4 or less by

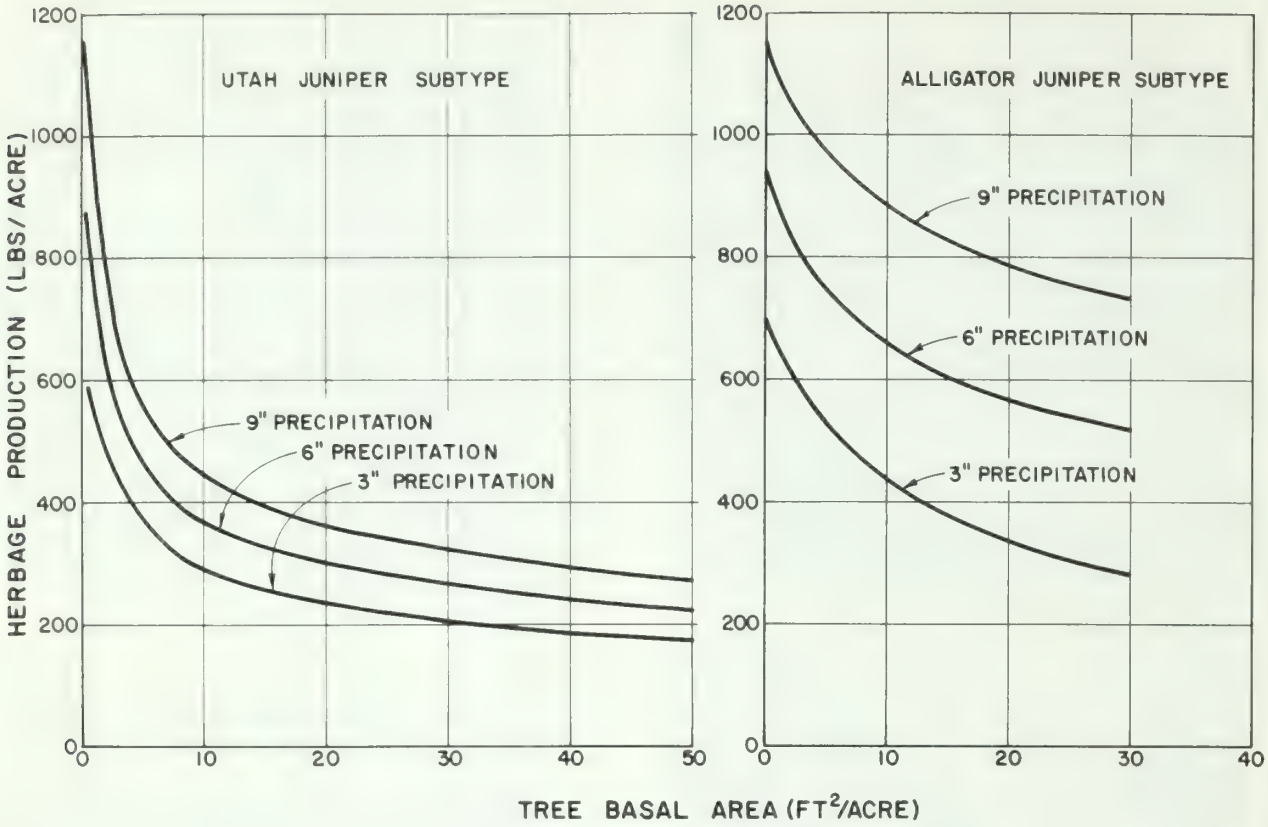

Figure 12.—Relationship of herbage production to tree basal area and summer precipitation in the two pinyon-juniper subtypes.

1964. The mean density from the mid-1960's to the early 1970's has been about two deer per section.

Elk make little use of the Utah juniper subtype on Beaver Creek except during extremely wet winters. The mean annual elk density of the alligator juniper is approximately one per section.

The forage plants on untreated areas that are most preferred by deer include, in order of contribution to the diet (Neff 1974):

	Percent of diet
Mountainmahogany	21
Eriogonum, Wright	9
Oak, shrub live	6
Cliffrose	5
Oak, Gambel	4
Ceanothus, desert	4
Lettuce, prickly	3
Squirreltail, bottlebrush	2
Buckthorn, hollyleaf	2
Bundleflower, James	2

Additional desirable plants such as crested wheatgrass, pubescent wheatgrass, yellow sweetclover, and clover are often seeded in conjunction with land treatments.

Production of preferred forbs, half-shrubs, and shrubs averages approximately 60 pounds per acre in the Utah juniper subtype and 90 pounds per acre in the alligator juniper subtype.

Forbs, half-shrubs, and shrubs, which are moderately to highly preferred by deer (Neff 1974), increased significantly as a result of two of the three treatments (table 8). The largest increase came on watershed 3 which had the least cover of perennial grasses.

The effect on wildlife cover also appears to be important. The one vegetation treatment on Beaver Creek which deer have tended to avoid is the felling treatment, even though the production of preferred forage increased somewhat. The situation on this watershed was unique in that the pinyon-juniper cover surrounding it had been removed in the late 1950's. The treatment had the effect of removing an island

Table 8.--Summary of treatment effects on forbs and shrubs preferred by deer on the two pinyon-juniper subtypes, Beaver Creek watershed

Watershed, by subtype, treatment, and year treatment completed	Deer forage production[1]		Level of significance[2]
	Untreated conditions	Response due to treatment	
	Pounds per acre		
UTAH JUNIPER SUBTYPE:			
Watershed 1-- Cabled, slash burned 1963	40	90	NS
Watershed 3-- Herbicide, no removal or burning 1968	83	[3]342	0.05
ALLIGATOR JUNIPER SUBTYPE:			
Watershed 6-- Felled, no burning, regrowth restricted 1965	79	41	0.10

[1]See table 7 for method of calculation.
[2]NS indicates nonsignificance at the 0.15 level.
[3]Beginning with second posttreatment year.

of cover (standing trees) surrounded by a large clearing. Thus, big game apparently avoid this particular area because of a lack of cover, even though a fair amount of slash remains. The same treatment on a watershed surrounded by live pinyon-juniper might have produced a far different result (Neff 1972b).

Deer use of watershed 1 remained essentially unchanged after the cabling treatment. Even though the watershed is up to one-half mile across, deer use was uniform across the area. Apparently there was sufficient shrub live oak and other low cover to satisfy the deer during the periods they ranged the large clearings (Neff 1972a).

The posttreatment deer use of herbicide-treated watershed 3 was moderately light, but it was considered to be a positive response because it increased annually following treatment (Neff 1972b). This response is apparently the result of greatly increased production of preferred forage (table 8), and the retention of cover (standing dead trees).

Of special importance to deer on this winter range is the increase in supply of late winter and early spring feed (personal communication with Don J. Neff, Ariz. Game and Fish Dep., Flagstaff) in the form of early grasses and preferred forbs on watershed 3. In 1972 the production of early feed was over four times that of the control watershed, or nearly 250 pounds per acre.

Elk use of the Beaver Creek pinyon-juniper watersheds has been too light to adequately assess their reaction to treatments. The responses of other wildlife species to the pinyon-juniper treatments have not been evaluated; an intensive wildlife evaluation program was initiated on the Beaver Creek ponderosa pine watersheds in 1972 (Brown and others 1974). Many smaller wildlife species will respond more strikingly than deer, however. A great many species of birds, for example, forage for food primarily in tree foliage (Balda 1969). When the trees are removed, these species will go elsewhere, and be replaced by ground-feeding species. Good populations of mourning doves, a species highly valued by bird hunters, are often observed on cabled areas.

Efficacy of Herbicide Applications

Herbicide was broadcast by helicopter on about 300 acres of watershed 3 in August 1968. Twenty acres were not treated. A 40-acre buffer strip between watersheds 2 and 3 was treated by spraying individual trees with backpack, motorized mist blowers. A commercially available mixture of triisopropalamine salts of picloram and 2,4-D was applied at the rate of 2½ pounds of picloram and 5 pounds of 2,4-D in a volume of 10 gallons per acre with a water carrier. The application rates were excessive for killing the junipers, but were used to aid studies of picloram residue in soils and runoff water. Picloram was used because of its promise of possible widespread use, based on other studies in juniper control.

On the entire watershed 83 percent of the Utah junipers were killed, including 96 percent killed on the broadcast area, 70 percent on the individual-tree buffer area, and very little damage on the untreated areas. On the treated areas the surviving trees either contained small amounts of live foliage or were small trees growing under the protective canopy of larger trees. Pricklypear cactus was severly damaged and has not recovered after several years. Shrub live oak and pinyon were severely damaged initially, but showed marked recovery within 2 or 3 years. Cliffrose was moderately damaged, but recovered quickly. Side-oats grama and other established perennial grasses were undamaged. Sulphur eriogonum and rough menodora were slightly damaged, but both of these, along with broom snakeweed, had been severely damaged by an earlier application of 2,4-D and 2,4,5-T esters. The remaining broom snakeweed was killed by the picloram-2,4-D application.

Numerous annual forbs and grasses invaded the watershed after the picloram-2,4-D treatment, although by 1972 perennial grasses, especially side-oats grama, were becoming more apparent over much of the watershed. Some of the annual forbs grew exceptionally large during the initial 2 years after treatment. Sunflowers, for example, which normally grow 3 or 4 ft tall along the roadsides, grew to 10 ft or more on the treated areas. This unusual growth may have

been due to increased moisture available, and possibly nutrients released by the dead junipers.

Forbs showed marked symptoms of picloram damage during midsummer of the first year, indicating the picloram was below the initial foot or so of the soil surface. Symptoms were slight by the third year and were not observed during the fourth year after treatment, indicating the picloram had disappeared from the root zone of the annual forbs.

The net effect of the herbicide treatment on vegetation was to convert a juniper-dominated tree stand to a stand of annuals. Usually, conversion by mechanical means has changed tree stands into half-shrub stands dominated by snakeweed. Small plot tests at other locations on Beaver Creek indicate the response of watershed 3 to herbicidal vegetation control is typical of the Utah juniper type. Perennial plants should become established eventually without the snakeweed stage of secondary succession. The presence of both spring- and summer-growing annuals indicates the possibility of producing both spring- and summer-growing perennials in these areas. How this growth pattern would affect water yields is not known.

Picloram concentration of surface runoff waters was determined during each flow period following treatment. The highest concentration detected was 0.32 p/m (part per million) during the initial flow after treatment. By the first spring after application, picloram concentrations were less than 0.01 p/m. No picloram has been detected in runoffs since October 1971.

It is estimated that about 1.3 percent of the picloram applied has left the watershed in runoff. Of this, 90 percent left within the first 7 months after treatment, during which time 13.2 inches of precipitation fell and about 14 acre-ft of water had run off the treated watershed. By the time the last picloram was detected, 58 inches of precipitation had fallen and 46.8 acre-ft of water had left the watershed. On one occasion picloram was detected 3.5 miles downstream, but at a concentration of only 0.002 p/m (minimum detectability is 0.001 p/m). Usually, picloram was not detected further than one-fourth mile downstream. There seemed to be little difference in picloram concentration due to type of runoff (snowmelt versus storm flow). Samples taken during flow periods gave similar results throughout the flow period.

These results are similar to those of high-rate applications of picloram in other studies. Lower rates of application would yield lower amounts of picloram in the runoff water, and for shorter periods.

The individual-tree treated area always had lower amounts of picloram in the runoff water than the broadcast area. The maximum picloram concentration detected from this area was 0.19 p/m during the initial flow period after treatment; within a year picloram was barely detectable in the runoff and has not been detected in flows since February 1971.

Picloram in the soil has declined to barely detectable amounts within 4 years. The initial amounts averaged 2.5 pounds of picloram per acre in a 4-ft soil mantle; within 3 years this was reduced to about 0.8 pound, and within 4 years to less than 0.02 pound. This reduction was reflected by the forbs growing on the watershed. During the initial year after treatment, forbs showed marked symptoms of picloram damage by midsummer. During the second and third summers these symptoms became less pronounced and occurred later in the summer. Very few symptoms appeared during the fourth summer. Results have been similar in other studies of high-rate application. With lower application rates, the picloram disappears from the soil much more quickly.

It must be remembered that the rate of application of the picloram was excessive for juniper control, and the inclusion of 2,4-D in the treatment was due to material availability not to increase the degree of juniper control. Less than a pound of picloram would be sufficient to control the Utah juniper. This lower rate should be competitive, costwise, with mechanical methods. Other herbicides can control junipers, but, like picloram, they are not presently registered for use except in experimental studies.

After the alligator junipers were felled on watershed 6 in the summer of 1965, polychlorinated benzoic acid in diesel oil was sprayed onto the stumps of all trees under 16 inches in diameter and on larger trees as needed to reduce sprouting. Shrub live oak stumps were treated with pelleted fenuron in 1965. Gambel oaks were treated with 2,4,5-T in diesel oil before bud break in the spring of 1966 (Brown 1971).

About half the stumps of alligator juniper under 16 inches diameter, the size class most likely to sprout, were killed by the polychlorinated benzoic acid treatment. About a fourth of the stumps of this size class were missed and untreated, and about another fourth had been poorly treated and sprouted. Shrub live oak showed little damage from the initial fenuron treatment, with indications of poor herbicide distribution around the oak clumps.

The residual juniper sprouts, Gambel oak sprouts, and shrub live oak were treated with a mixture of picloram and 2,4-D at a concentration of 1 pound picloram and 2 pounds 2,4-D per 10 gallons of water in August and September 1968. Kill of the alligator juniper was satisfactory. That of the oaks was variable.

Benefit-Cost Analysis

The basic intent of this Paper is to examine the impact of vegetation manipulation on multiple uses of the land in the pinyon-juniper type, with emphasis on the Beaver Creek Pilot watersheds. Effects of watershed treatments on surface water yield, livestock forage production, and big-game habitat are summarized in table 9. The effects have not been very impressive. Impacts of these treatments on other multiple uses of these lands, such as recreation and esthetics, have not yet been discussed.

Recreation use is limited primarily to hunting, although there are other forms of dispersed recreation such as four-wheel-drive and motorcycle pleasure riding, horseback riding, and hiking. The concern for esthetics would come primarily from these users unless the treatments would be in a travel influence zone. Complete overstory removal, as on watersheds 1 and 6 (cabling and felling treatments), would be detrimental both recreationally and esthetically. Most people, however, would probably consider a partial removal properly designed to be a plus from both recreation and esthetic standpoints.[6] Presently, watershed 3 (herbicide treatment) would be preferred by hunters because it is attractive to deer, but from an esthetic viewpoint it would probably be disliked. The negative visual aspects of the defoliated trees were not adequately offset by the new growth of herbaceous plants.

Since incremental changes in water yield and forage production can be productively used, the amount of these benefits should be identified. The value of additional water can be analyzed from two viewpoints—those of the primary user, and the Salt River Valley Water Users Association which administers the dams in the Salt and Verde Basins and handles water distribution. Additional water production from the Salt-Verde Basin will be demanded by irrigated agriculture for feed grain and forage produc-

[6]There is a cooperative study now underway at the University of Arizona entitled: "Development and validation of an unbiased method to quantify natural beauty of forest landscapes" that will provide a procedure to measure the esthetic dimension.

Table 9.--Summary of treatment effects on surface water yield, livestock forage production, and big-game habitat on the two pinyon-juniper subtypes, Beaver Creek watershed

Watershed, by subtype, treatment, and year treatment completed	Post-treatment	Products		
		Water yields	Livestock forage	Big-game habitat
	Yrs		*Lb/acre*	
UTAH JUNIPER SUBTYPE:				
Watershed 1--Cabled, slash burned 1963	9	No significant change	+180	+preferred plants (deer) -cover[1] No apparent effect on deer use
Watershed 3--Herbicide, no removal or burning 1968	4	+1/2 inch	+65	+preferred plants (deer) No apparent effect on cover +deer use of watershed
ALLIGATOR JUNIPER SUBTYPE:				
Watershed 6--Felled, no burning, regrowth restricted 1965	7	No significant change	+130	+preferred plants (deer) -cover[2] -deer and elk use

[1]Because watershed 1 was surrounded by Utah juniper and considerable shrub live oak cover was present nearby, reduction in tree cover on the watershed was not a severe deterrent to deer use.

[2]The alligator juniper surrounding watershed 6 had been removed several years prior to treatment and little lateral cover was present, which had a negative effect on deer use.

tion. All other users of water such as municipal, industrial, and high-value crops already have their demand satisfied with existing supplies. Based on 1972 conditions, the ability-to-pay value for water used in irrigating feed grain and forage crops would have been $11.20 (T. Brown et al. 1974). The value of additional surface water to the Salt River Project is the savings in costs resulting from the replacement of pump water. For the first 25,000 acre ft, this amount is estimated at $10.30 per acre-ft (Salt River Project cost records, 1972) and consists of savings in operating and capital costs, and reduction in depletion rate of ground-water table. An additional value which must be added is the power revenue the water would generate if the additional flow came in above Roosevelt Dam. In 1972, this would have amounted to $2.48 per acre-ft. Based on the above information, the maximum primary value of additional water is $13.68 per acre-ft delivered to the user. Applying that value to the half-inch increase on watershed 3, we have a value of 57 cents per acre per year. This assumes that all onsite increases in water yield would reach the user, which is not likely.

Before forage production can be measured in dollar terms, it must first be converted to grazing capacity. A conservative conversion commonly used is 1,000 pounds of forage per AUM. If we assume the range is grazed seasonally rather that yearlong, however, so that shattering loss is reduced, 750 pounds of forage disappearance per AUM (ovendry) is more realistic. Based on 40 percent utilization, the following gains in potential grazing capacity could be expected:

Watershed	AUM / acre
1	0.11
3	.03
6	.07

There are several ways to identify the incremental value of increased carrying capacity. These include the grazing fee paid, the capitalized value of Forest Service permits plus the grazing fee, the comparable private lease rate, and the marginal value of additional grazing capacity to existing ranches. For these watersheds the latter approach is the best, since a rancher currently operates in this area. Not all ranch costs increase proportionately with the addition of more cattle, however, so the costs per AUM are less than average of the ranch's herd. Examples of costs which do not increase proportionately are property tax, insurance, utilities, and building depreciation. To arrive at an expected monthly return for the additional cattle, a representative market price needs to be identified and structural improvement costs and operating costs deducted. This was done in a recent study (O'Connell and Boster 1974) for 1972 conditions; the net returns per AUM amounted to $5.82.

Values determined by the other methods are approximately the following (1972 conditions):

Forest Service grazing fee[7]	$0.72 per AUM
Forest Service grazing fee plus capitalized value of permit[8]	2.30 per AUM
Comparable private lease rate[9]	3.94 per AUM

Several publications discuss the merits of these different approaches in detail (Dickerman and Martin 1967, Martin and Jefferies 1966, Regional Research Project W-79 1968, Smith and Martin 1972).

Applying the $5.82 figure to the gains in grazing capacity results in per-acre returns of 64 cents per acre for watershed 1, 17 cents per acre for watershed 3, and 41 cents for watershed 6.

If 7.0 percent is the appropriate capitalization rate, a 64-cent annuity would capitalize to $9.14 per acre (64 cents ÷ .07 = $9.14), a 17-cent annuity would capitalize to $2.42 per acre, and a 41-cent annuity would capitalize to $5.86 per acre. Considering the returns discussed, the **maximum** allowable per-acre treatment costs are $9.14 for watershed 1, $10.57 for watershed 3,[10] and $5.86 for watershed 6. The noneconomic effects would not tend to enhance the feasibility of the treatment.

The capitalized values, as calculated above, represent allowable costs for initial treatments and any followup maintenance that may be required. If initial cost was $15.00 per acre and a $1.50 per-acre maintenance cost was required every 10 years, the total cost (1972 value) would be $16.49. To cover a maintenance cost of $1.50 every 10 years, a fund of $1.49 would have to be set aside at 7.0 percent interest. The accumulated interest would be sufficient to cover a 10-year periodic maintenance cost of $1.50 into perpetuity.

[7]*Based on 1972 grazing fees on the Coconino National Forest.*

[8]*Based on information developed by Martin and Jefferies (1966) and updated to 1972.*

[9]*Based on commercial rate the Forest Service charges; it is developed annually by the USDA Statistical Reporting Service, and represents comparable private lease rates in the Western States in 1972.*

[10]*The 57-cent annuity for expected water-yield increases on watershed 3 was also capitalized at 7.0 percent interest and equaled $8.14.*

The actual per-acre costs were $19.41 (Worley and others 1965) for watershed 1, $36.90 for watershed 3,[11] and $45.00 (Miller 1971) for watershed 6. Thus juniper control is not economically feasible for areas that have responses similar to these watersheds.

The range carrying capacity of the experimental watersheds appears to be below the average for conditions in the Southwest. According to 1972 figures,[12] average grazing capacities of pinyon-juniper ranges (defined as having at least 75 percent pinyon-juniper cover type) on the National Forests of Southwest varied from 0.25 AUM per acre for ranges in good condition to 0.04 AUM per acre for ranges in poor condition. Even after juniper is removed, the carrying capacity would be 0.23 AUM per acre for watershed 6 and 0.13 AUM for watershed 1 (assuming 40 percent utilization throughout the watersheds).

A more successful juniper control project would expect to have increases in forage production of from 400 to 600 pounds per acre (ovendry) beginning 2 to 3 years after conversion. Some areas where this increase has occurred include the Canjilon project on the Carson National Forest and the Bar T Bar, 13 Mile Rock, Buckhorn, and Deadwood projects on the Coconino National Forest. Discussions with range managers of the Fort Apache Indian Reservation indicate these yield increases have been attained on some of their better projects also.

Using the same conversion factors discussed above and assuming an increase in forage production of 500 pounds per acre, the gain in potential grazing is 0.27 AUM/acre. This expected increase in grazing capacity is similar to that experienced on the Bar T Bar Ranch for 8 years following conversion. Using a value of $5.82 per AUM and assuming cattle were put on the converted area 3 years after conversion, the capitalized value would be $19.15 per acre. Other ranching benefits of removing junipers are reduced labor costs and faster weight gain of yearlings. Cotner and Kelso (1963) reported an 18-cent gain per acre for these benefits. Updating these figures to 1972 (which brings them to 35 cents per acre) and capitalizing them, these added benefits would amount to $4.33 per acre. The total benefit to ranching amounts to $19.15 + $4.33 = $23.48 per acre (7.0 percent interest rate) for the more successful conversions. If a 10.0 percent interest rate is used, the total benefit is $15.56 per acre.

The surface water yield response of the experimental watersheds appears to be typical; there is no strong evidence of surface water yield improvement from treating pinyon-juniper watersheds.

Other effects of conversion that should be evaluated are impacts on water quality, sediment yields, wildlife habitat, and esthetics. If the conversion is done and maintained properly and if good range management practices are followed, there can be plus effects for some of these factors. The problem is the number of "ifs". The evidence to date has been mixed.

Beaver Creek costs are atypical because of the small size of the watersheds and experimental nature of the treatments. The most complete cost analysis on juniper control in the Southwest was done by Cotner (1963). He found that number of trees per acre and tree height explained most of the site variation in costs. Based on Cotner's analysis and using 1972 cost estimates, a bulldozing operation would cost between $9 and $13 per acre for pushing and piling a moderately dense stand of 125 trees per acre that are 12 to 15 ft high. Followup cleaning and slash burning costs vary from $2 to $4 per acre (Forest Service records, Worley and Miller 1964), and seeding costs are estimated at $4.20 per acre (Warskow 1967, updated to 1972). A minimum maintenance allowance would be $1.50 per acre every 10 years. Pulling all these items together—pushing and piling, followup cleaning and burning, seeding, and maintenance—a moderately priced juniper conversion for an operational size project would cost about $19.69 per acre (1972 conditions).

Other major mechanical methods used for controlling juniper include cabling and the use of a tree crusher. Cabling was used extensively in the fifties and the early sixties, but most of the good sites for cabling have already been converted. The cost for cabling is about half that of pushing and piling, but it is not as effective. Although a tree crusher is the most effective, it cannot be used in rocky areas, which includes much of Arizona. The cost is slightly higher than pushing and piling.

Although herbicide treatment is the only method that increased water yield from the juniper type, current restrictions on use of herbicides preclude consideration of them in the immediately foreseeable future.

The literature review and the above analysis leads us to conclude that, based on 1972 technology, costs, and values, identifiable economic benefits and costs come out about even for the

[11] *Estimated from local USDA Agricultural Research Service records.*

[12] *Springfield, H.W. Characteristics and management of southwestern pinyon-juniper ranges. (Manuscript in preparation, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

more successful juniper control projects. At a 7.0 percent interest rate there is a net positive difference of $3.79 per acre, while at a 10.0 percent interest rate the difference is negative (-$4.13). This means that for the more successful projects, benefits will just cover costs. Each project should be examined on its own merits, however.

Some other considerations that should be examined on individual projects include whether limited investment dollars can bring a higher return elsewhere, and whether the juniper control project can be made a multiproduct sale.

Conclusions

These conclusions apply specifically to the Arizona pinyon-juniper vegetation type on volcanic-derived soils along the Mogollon Rim. Evidence in the literature suggests, however, that similar results and conclusions may also be expected in other southwestern areas.

- Conventional mechanical methods of pinyon-juniper removal cannot be expected to increase water yields in the Utah juniper subtype.
- Overstory removal by herbicide appears to be the only vegetation treatment that is likely to increase water yield from Utah juniper watersheds. Picloram effectively controlled the pinyon-juniper overstory and changed the successional pattern of herbaceous plants. Only 1.3 percent of the picloram left the watershed in runoff water, and it ceased to be detectable in the water within 3 years after application. Picloram was barely detectable in the soil mantle after 4 years.
- The areas of low tree densities in the alligator juniper subtype do not show promise for increasing water yield.
- The felling treatment on watershed 6 could have been advantageously modified to retain the large mature and overmature alligator juniper trees. This modification would have resulted in sizable cost savings (Miller 1971, Miller and Johnsen 1970), provided an esthetically appealing savanna aspect, retained more wildlife cover, and may have maintained greater long-term early forage on these spring-fall ranges (Clary and Morrison 1973).
- There has been no meaningful change in sediment yields as a result of overstory removal. Five of the seven pinyon-juniper water-quality samples met drinking water, aquatic life, and irrigation water standards. Two samples were slightly high in iron to conform to the drinking water standard. Apparent differences in water quality among watersheds were not validated by statistical methods because of inadequate sample size.
- Overstory removal in the Utah juniper subtype will result in a severalfold increase in herbage production. The value of this increase for livestock or wildlife use is highly variable. The potential increase in livestock carrying capacity on many Utah juniper areas is nearly 0.5 AUM per acre, but this potential is rarely approached. An increase of about 0.21 to 0.32 AUM per acre is indicated for the more successful pinyon-juniper conversion projects. Much lower increases are typical when pinyon-juniper conversions are attempted on low potential sites or when poor seeding techniques are used.
- The response by deer to the pinyon-juniper watershed treatments was, on the average, neutral. All treatments increased the production of preferred plants, but cover should be available nearby for the deer to maintain use of the areas. Deer have responded positively to the herbicide treatment, which resulted in a fourfold increase in palatable herbaceous forage plants and maintenance of relatively heavy cover. Elk use of the pinyon-juniper watersheds was not heavy enough to allow an evaluation of their response. The response of other wildlife species has not been measured.
- Current restrictions on herbicide use (the only treatment that increased water yield) and the negative esthetics of standing dead trees may limit juniper control to mechanical methods for the foreseeable future. Since mechanical methods are not likely to produce measurable water yield increases, the only economic returns are from range values. Analysis of a number of pinyon-juniper conversion attempts suggests that under 1972 economic conditions the more successful projects just about break even from a benefit-cost standpoint. Projects which are less successful than the best will produce a negative net return. Therefore, considerable planning and forethought should precede any future pinyon-juniper conversion attempt.
- Experience with herbicides on Beaver Creek and with fire elsewhere suggests that these two methods may be the most fruitful areas for future juniper control research from the combined standpoints of water production, forage production, deer response, and economics.

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Common and Botanical Names of Plants Mentioned

Common Names	Botanical Names
	Grasses
Grama, side-oats	*Bouteloua curtipendula* (Michx.) Torr.
Lovegrass	*Eragrostis* spp.
Sprangletop, red	*Leptochloa filiformis* (Lam.) Beau.
Squirreltail, bottlebrush	*Sitanion hystrix* (Nutt.) J.G.Smith
Wheatgrass, crested	*Agropyron desertorum* (Fisch.) Schult.
Wheatgrass, pubescent	*Agropyron trichophorum* (Link) Richt.
Wheatgrass, western	*Agropyron smithii* Rydb.
	Forbs and Half-Shrubs
Bundleflower, James	*Desmanthus cooleyi* (Eaton) Trel.
Clover	*Trifolium* spp.
Conyza	*Conyza canadensis* (L.) Cronq.
Eriogonum, sulfur	*Eriogonum cognatum* Greene
Eriogonum, Wright	*Eriogonum wrightii* Torr.
Goosefoot	*Chenopodium* spp.
Lettuce, prickly	*Lactuca serriola* L.
Menodora, rough	*Menodora scabra* A. Grey
Russianthistle	*Salsola kali* L.
Snakeweed, broom	*Gutierrezia sarothrae* (Pursh) Britt. & Rusby
Spurge	*Euphorbia* spp.
Sunflower, common	*Helianthus annuus* L.
Sweetclover, yellow	*Melilotus officinalis* (L.) Lam.
	Shrubs
Buckthorn, hollyleaf	*Rhamnus crocea* Nutt.
Cactus, pricklypear	*Opuntia* spp.
Ceanothus, desert	*Ceanothus greggii* A. Grey
Cliffrose	*Cowania mexicana* D. Don
Mountainmahogany	*Cercocarpus* spp.
Oak, shrub live	*Quercus turbinella* Greene
	Trees
Juniper, alligator	*Juniperus deppeana* Steud.
Juniper, one-seed	*Juniperus monosperma* (Engelm.) Sarg.
Juniper, Utah	*Juniperus osteosperma* (Torr.) Little
Oak, Gambel	*Quercus gambelii* Nutt.
Pine, ponderosa	*Pinus ponderosa* Laws.
Pinyon	*Pinus edulis* Engelm.

Clary, Warren P., Malchus B. Baker, Jr., Paul F. O'Connell, Thomas N. Johnsen, Jr., and Ralph E. Campbell.
1974. Effects of pinyon-juniper removal on natural resource products and uses in Arizona. USDA For. Serv. Res. Pap. RM-128, 28 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Results from six treated and control watersheds, along with other results from the southwestern pinyon-juniper type, suggest that: (1) mechanical methods of pinyon-juniper removal are not likely to increase water yield; (2) removal of pinyon-juniper overstory by herbicides can increase water yield; (3) there has been no statistical verification of changes in flood peaks or water quality due to treatment; (4) herbage yields increase after virtually all pinyon-juniper treatments, but potential livestock carrying capacity varies greatly due to differences in plant composition; (5) the response by deer to these treatments is, on the average, neutral; (6) the more successful conversion projects just about break even from a benefit-cost standpoint under 1972 economic conditions.

Keywords: *Pinus edulis, Juniperus* spp., watersheds.

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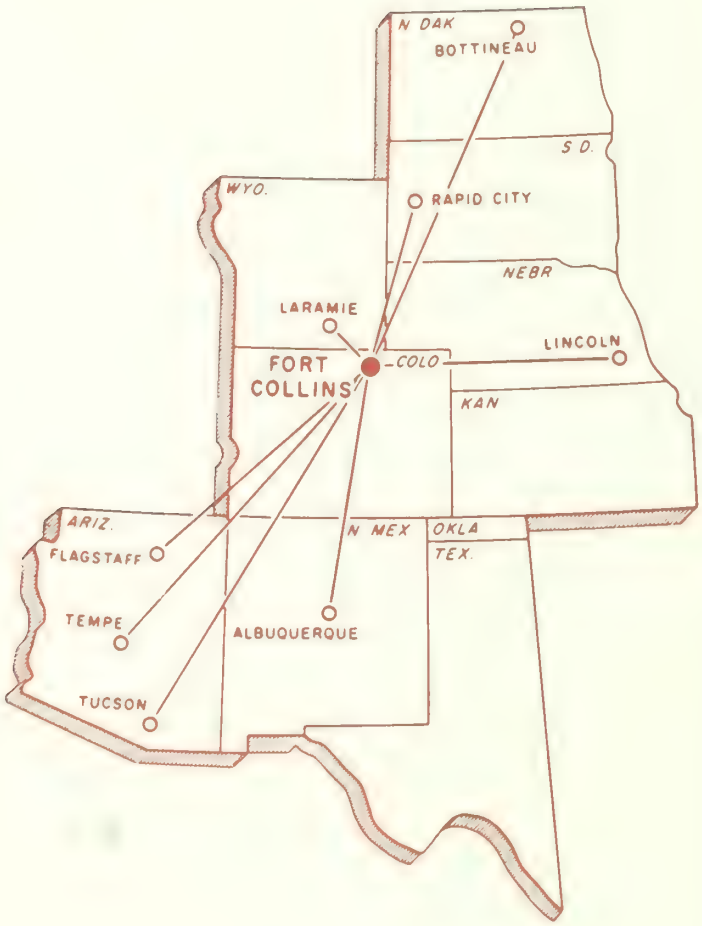
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Opportunities for
Increasing Water Yields and Other Multiple Use Values
on Ponderosa Pine Forest Lands

Abstract

Multiple use productivity is described for watershed lands in the ponderosa pine type of Arizona, with special emphasis on the Beaver Creek Pilot Watershed near Flagstaff. Yields of timber, herbage, and water under past management are reported, along with information on wildlife values, esthetics, flood and sedimentation hazards, and water quality. Changes in productivity and environmental quality are then described following five experimental land treatments including livestock grazing and various levels of forest thinning and clearing. Preliminary analytical procedures for predicting treatment responses and costs allow the user to estimate the tradeoffs in production and environmental quality. Some further research needed for bringing these and other response models to operational capability is described.

Keywords: Water-yield improvement, forest management, multiple use, *Pinus ponderosa*.

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USDA Forest Service
Research Paper RM-129

December 1974

Opportunities for Increasing Water Yields and Other Multiple Use Values on Ponderosa Pine Forest Lands

by

Harry E. Brown, Malchus B. Baker, Jr., James J. Rogers,
Warren P. Clary, J. L. Kovner, Frederic R. Larson,
Charles C. Avery, and Ralph E. Campbell[1]

[1]*Central headquarters maintained at Fort Collins, in cooperation with Colorado State University. Brown, Principal Hydrologist, is now Group Leader for Watershed and Aquatic Habitat Research, Washington, D.C. Baker, Associate Hydrologist, Rogers, Research Hydrologist, Clary, Principal Plant Ecologist, Larson, Associate Silviculturist, Avery, Associate Hydrologist, and Campbell, Research Soil Scientist, are located at the Station's Research Work Unit at Flagstaff, in cooperation with Northern Arizona University. Kovner, Principal Biometrician, is located at the Station's central headquarters.*

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Introduction

This report documents the background of water yield and multiple use research in the ponderosa pine type in Arizona, and sets forth the objectives of the program initiated on the Beaver Creek Pilot Watershed on the Coconino National Forest near Flagstaff to carry out the research. It characterizes the Beaver Creek area in physical terms, and describes its multiple use production under present management. This section is followed by an updated presentation of results of the various treatments being pilot tested. Models are described that eventually will be incorporated into a multiple use management planning system of broad applicability. Interrelationships of the various products are discussed and implications are pointed out indicating the best general forest density levels to achieve various management objectives. Finally, needed research is described to provide better management tools.

Background

In the mid-1950's, water-user and ranching groups in the Salt-Verde Basin called attention to the possibility of treating watersheds to increase irrigation water yields and provide more grass for grazing. In response to these concerns, the Chief of the Forest Service approved in August 1956 the "Arizona Water Management Project, Beaver Creek." The objectives of the project were to observe the effects of vegetative changes on water yield, soil, forage, fish, wildlife, and recreation, and to determine whether these changes increased the risk from fire, insects, and disease. The work in 1956-57 was to be an action watershed improvement program involving clearing of 4,000 acres of juniper and silvicultural thinning of 1,200 acres of ponderosa pine.

During this period, a staff of watershed management experts studied the economic feasibility of obtaining additional water for irrigation from the watersheds of Arizona. The report resulting from this study, known as the "Barr Report," was released in December 1956 (Barr 1956).

The Arizona Water Resources Committee in February 1957 recommended a program of action and research, the purpose of which was to find out if modification of vegetation could produce more water on the Salt-Verde Watershed. Specific recommendations were made for projects in spruce-fir, ponderosa pine, juniper, chaparral, and streambed vegetation (Brown 1970).

The Beaver Creek watershed was chosen to represent the juniper and pine types. In the period 1957-62, stream gages were built on 18 small watersheds of 66 to 2,036 acres: three in the Utah juniper type, three in the alligator juniper type, and 12 in the ponderosa pine type. Stream gages were also built on two large watersheds, Woods and Bar M, to provide an opportunity for testing composite treatments developed on the small watersheds. Sediment-measuring installations of new design were constructed on nine of the watersheds. Also, a network of precipitation gages was installed. Timber, range, and wildlife were inventoried, the latter by the Arizona Game and Fish Department.

Objectives of the Beaver Creek Watershed Evaluation Program

The general objective of the project as assigned in the 1960's was to evaluate land management measures designed to increase water yields. While water yield was to receive major consideration, changes in forage and timber production, wildlife populations, recreational value, and erosion and sediment movement were also to be evaluated. Costs and benefits of the various treatments were to be studied so that the total project could be evaluated. These objectives, maintained until 1971, resulted in six pilot treatment tests on pine watersheds and three in the juniper.

In 1971 an Interdisciplinary Team assigned by the Chief of the Forest Service reviewed the Project and recommended the objectives be

changed to read as follows:

1. To develop multiple use production data for alternative land management practices, and determine their ecological and environmental impacts.
2. To develop, test, and refine physical product models that will estimate responses to management activities for use in decisionmaking in the Southwest.
3. To develop and test an economic evaluation and planning model.
4. To pilot-test and demonstrate on an operational scale the physical product and evaluation-planning models and other management procedures thus developed.
5. To develop from the physical and economic models a series of management models with broader geographic, economic, and environmental application potential.
6. To publish a report explaining the physical responses to land management treatments, procedures recommended for planning management programs, and how a balanced land management program in the Salt-Verde Basin might affect resource outputs and environmental quality.

This report will document the progress that has been made toward meeting these objectives. In brief, it will show that the objectives of the sixties and the first objective of the seventies have largely been met. The modeling and large-scale pilot testing objectives of the seventies will be discussed, although only limited results can be presented.

Physical Characteristics and Productivity of the Ponderosa Pine Type

Ponderosa pine forests occupy about 4,282,000 acres in Arizona and 4,681,000 acres in New Mexico (Spencer 1966; Choate 1966). In the Salt-Verde Basin in Arizona they occupy more than 1,650,000 acres or 20 percent of the watershed (fig. 1); they produce nearly one-half of the total runoff of the Salt River (Barr 1956). The Beaver Creek watershed, to be characterized in this section, is about one-third ponderosa pine (fig. 2). Total area of Beaver Creek is about 275,000 acres.

Physiography of the Pine Type on Beaver Creek

A high plateau, sloping mesas and breaks, steep canyons, and valleys characterize the topography on Beaver Creek. Elevations in the pine type vary from about 6,800 feet to 8,000 feet. The bedrock underlying the area consists of igneous rocks of volcanic origin; below them are sedimentary rocks of Kaibab, Coconino, and Supai formations.

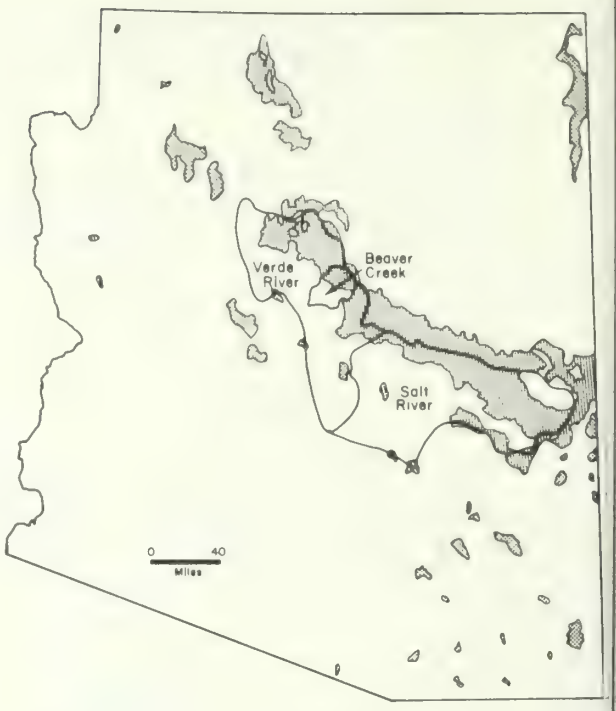

Figure 1.—The ponderosa pine type in Arizona.

Geology of the watershed was studied by Beus, Rush, and Smouse,[2] and Scholtz (1968). Their inventories included, in addition to rock types, identification of geologic features such as faults and fractures that can be quantified and used in water prediction models.

The soils, developed on basalt and cinders, are mostly silty clays and silty clay loams less than 2-1/2 feet deep. They are described in detail by Anderson, Williams and Creeze (1960) and Williams and Anderson (1967). To better predict the hydrologic properties of the soils, the relationships between physical and hydrologic characteristics of soils within the various soil management areas were studied in the laboratory by Rector (1969), Ryan (1969), and Thames.[3]

Hydrologic Characteristics of the Pine Type on Beaver Creek

This section briefly describes the hydrologic characteristics of the southwest ponderosa pine type, and in particular the Beaver Creek

[2]*Unpublished reports available at the Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

[3]*Thames, John L. A study to determine the hydrologic and physical properties of some Beaver Creek soils. Final report of a cooperative study between the Univ. of Ariz. and the Rocky Mt. For. and Range Exp. Stn., 331 p. Flagstaff, Ariz. 1969.*

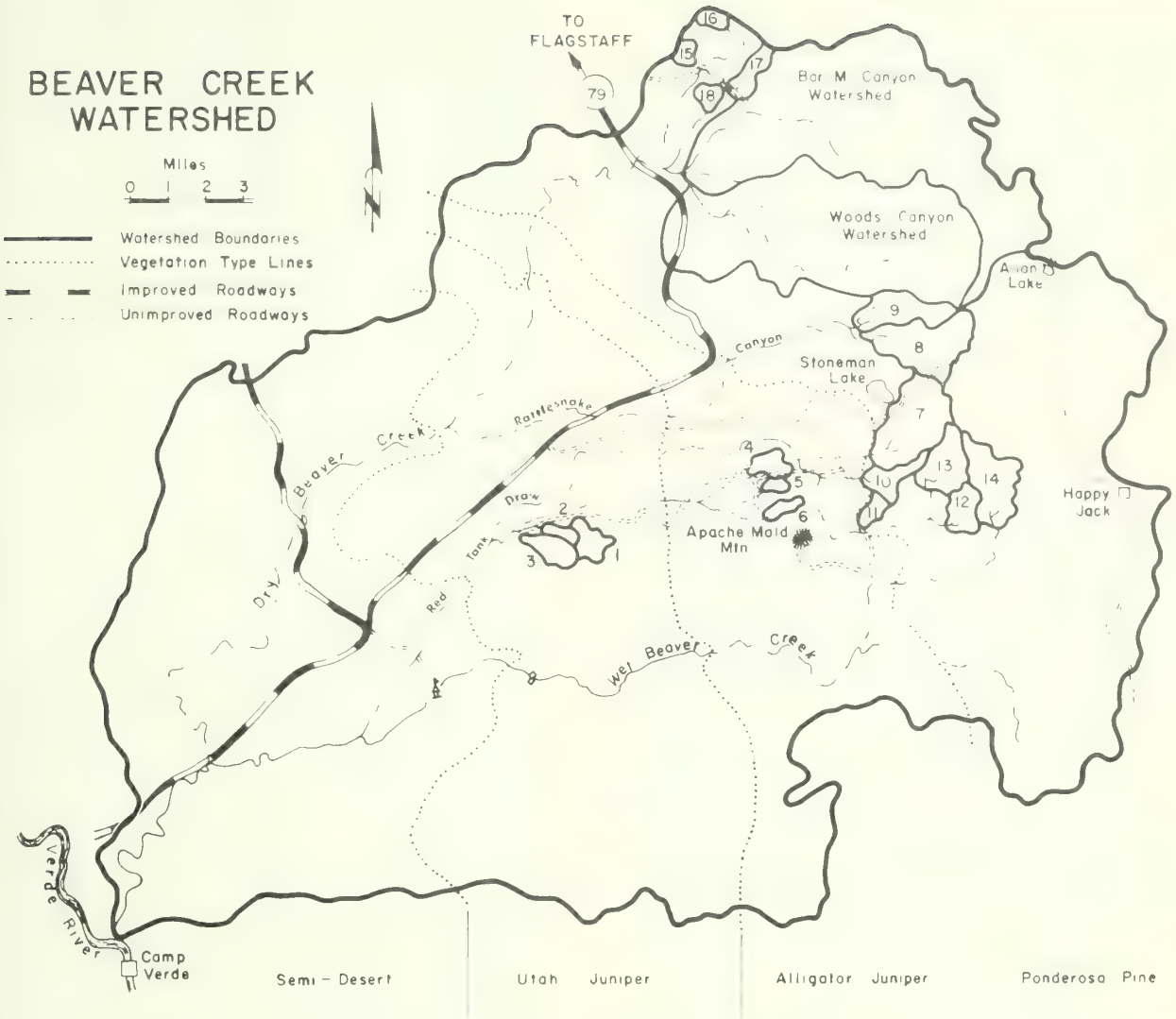

Figure 2.—The Beaver Creek Pilot Watershed.

watershed. It begins with a general description of the temperature and precipitation regimes, and then follows precipitation as it falls on a watershed to its eventual disposition as runoff, evaporation, transpiration, or subsurface flow.

Temperature.—The Beaver Creek watershed lies in the center of Arizona in what is called the plateau climatic region, which includes the Kaibab, Coconino, and Mogollon Plateaus and the San Francisco and White Mountains (Green and Sellers 1964). January temperature in the region averages 26° F and the July temperatures 66° F (Schubert 1974).

Climatic records of different kinds are presently being obtained at 50 locations in the pine type on Beaver Creek. At ten of the locations precipitation is recorded continuously. Temperature and humidity are recorded at three locations. Average annual temperature in the pine type has been 45° F. Monthly averages have been as follows:

	Maximum	Minimum	Mean
		(Degrees F.)	
October	64	30	47
November	52	23	37
December	44	15	29
January	44	14	29
February	45	16	30
March	49	19	34
April	56	24	40
May	67	31	49
June	76	37	57
July	83	48	66
August	78	47	63
September	73	41	57

These data are based on an average of 12 years of record from weather stations on Watersheds 8, 17, and Bar M.

Precipitation.—The ponderosa pine type in Arizona receives between 15 and 25 inches of precipitation annually (Schubert 1974). On Beaver Creek the average annual precipitation has ranged from 18 to 35 inches with an average of 25 inches on six representative watersheds. These watershed averages, based on 13 years of record, were determined by the Theissen method using 20 precipitation gages. Precipitation distribution throughout the water year is illustrated by these monthly averages for Watersheds 7, 8, 10, 13, 15, and 18:

	Inches
October	1.08
November	2.40
December	3.65
January	2.10
February	2.25
March	2.59
April	1.83
May	.65
June	.44
July	2.34
August	3.22
September	2.41
Average annual	24.96±0.61

There are two major precipitation seasons in the plateau region. The most important is during the winter — October through April. Sixty-four percent of the annual precipitation falls during these 7 months on Beaver Creek. The second is during the summer, particularly July through September, during which 32 percent of the annual precipitation falls.

Predictable atmospheric circulation patterns carry large quantities of moisture over the State and encourage precipitation. Moisture for most summer precipitation comes from the Gulf of Mexico. Occasional record summer rains in the past century have been associated with movements of tropical air into the State from the Gulf of California and the Pacific Ocean. Moisture for winter precipitation comes from the Pacific Ocean.

Average annual snowfall for 15 locations in the ponderosa pine forests of Arizona ranges from a low of 12 inches to a high of 94, with an annual mean of 46 inches (Schubert 1974). Snowfall is not consistent from year to year in this area. Fort Valley averages 91 inches, however in 13 out of 60 winter seasons less than 60 inches of snow fell. Snowfall during 34 percent of these winters averaged less than 1 foot per month for four consecutive months.

The snow regime as described by the SCS snow courses at Casner Park, Happy Jack, and Munds Park provide a usable estimate of the snow conditions on Beaver Creek. The 15-year average water equivalents at these locations on March 1 are 3.2, 4.4, and 2.7 inches, respectively, or 3.4 inches overall. This compares to 3.6 inches at Heber and Workman Creek, Arizona. The snow regimes on Beaver Creek are characteristic of locations along the Mogollon Rim; however, they are higher than pine areas away from the Rim such as Fort Valley, which has an average of 2.1 inches.

Snow regimes on Beaver Creek are quite variable and result in different runoff patterns and amounts. Most runoff is produced when there is a continuous snowpack from November through April. In these years there is often a continuous small flow of water from the pine watersheds, followed by a large runoff period in March or April. Often, major runoff occurs when rain falls on a snowpack. In Water Year 1966 there was almost continuous flow all winter as a result of intermittent storms which dropped mixed precipitation — both rain and snow — on a shallow snowpack. In Water Year 1972 a snowpack started to accumulate in November and built up till late in December when a rainstorm removed all of the snow, producing a large runoff event. A third type of snow regime is characterized by intermittent snowfall followed by a dry period in which the snowpack disappears. These typically light snowfall years yield little if any runoff since most of the water in the snow evaporates back to the atmosphere or infiltrates into the soil. In a fourth snow regime, very little snowfall occurs throughout the season. During these winters the snowpack seldom accumulates over a few inches, and results in little if any runoff.

Interception, stemflow, and throughfall.—Studies of rainfall interception by pole-sized ponderosa pine in central Arizona have shown that 11 to 25 percent of the summer rainfall is intercepted (U.S. Forest Service 1958). Of the net rainfall (throughfall plus stemflow), 71 to 88 percent reaches the soil as throughfall and 1 to 8 percent is transported to the soil as stemflow. Although little is known about interception of snow by ponderosa pine on Beaver Creek, Kittredge (1948) reported 22 percent interception by mature ponderosa pine in Idaho and 18 percent for young ponderosa pine in Colorado (Kittredge considered interception to include stemflow). Thus ponderosa pine apparently intercepts similar percentages of snow and rain.

Evaporation.—Studies of evaporation from forest floor litter under ponderosa pine in cen-

tral Arizona show that between 7 and 25 percent of the total summer rain is evaporated to the atmosphere (U.S. Forest Service 1959).

Studies of evaporation from snow under ponderosa pine in Arizona and New Mexico show that between 0.006 and 0.16 inch of water per day is lost to evaporation (U.S. Forest Service 1960). Thus a snow cover present for 2 months may lose as much as 5 inches of water by evaporation. In open areas within the forest, this amount would probably be greater.

Infiltration.—The major soil series in the ponderosa pine area on Beaver Creek are Brolliar, Siesta, and Sponseller. These soils are developed on parent materials of basalt and volcanic cinders. Their textures range from moderately fine to fine, and they characteristically have a slow rate of infiltration — 0.05 to 0.2 inch per hour when thoroughly wetted (Williams and Anderson 1967). These soils also have a layer that impedes downward movement of water. These characteristics are major factors in producing the surface runoff which comprises most of the water yield on the Beaver Creek watersheds.

Streamflow.—New techniques in streamgaging have been utilized on Beaver Creek to accurately measure the broad range of debris-laden discharges carried by the streams. A concrete trapezoidal flume was designed for use on the 18 small watersheds. The design was a modification of a Washington State College flume, adapted to Beaver Creek conditions (fig. 3).[4] Another was a new design for gaging discharges of several thousand ft^3/s (cubic feet per second) on Woods Canyon and Bar M (fig. 4; Brown 1969). H flumes have been constructed on 24 small homogeneous subwatersheds where flows are usually less than 15 ft^3/s (fig. 5).

The watersheds are organized into an experimental design to provide a basis for statistical evaluation of changes in streamflow. Watersheds within each vegetation type are paired, with some scheduled for treatment and others retained untreated as statistical controls. Following pretreatment calibration, one watershed in each pair is treated. These methods are described by Kovner (1956), Kovner and Evans (1954), and Wilm (1943).

Average annual streamflow from all untreated pine watersheds on Beaver Creek has varied from 0.2 to 16.4 inches with an overall average for the type of 5.3±0.5 inches per year (based on 14 years of record, through Water Year 1973). Ninety-three percent of this flow has come during the period October through April as a result of snowmelt or winter rains.

[4]*Robinson, A.R. Study of the Beaver Creek measuring flumes. Report to the Rocky Mt. For. and Range Exp. Stn. 14 p. Flagstaff, Ariz.*

Figure 3.—Concrete trapezoidal flume of the type used on Watersheds 1-18 on Beaver Creek.

Figure 4.—The Woods Canyon streamgage.

Figure 5.—Streamgaging installation used on subwatersheds.

Occasional summer storms produce flood flows of short duration. Although these floods do not contribute much to the total water yield they are a major factor in erosion and sedimentation.

Figure 6 illustrates the monthly distribution of streamflow and precipitation (based on 112 station years of record). For the year as a whole, 20 percent of the precipitation becomes streamflow. For the October-April period, streamflow is 28 percent of precipitation, and for May-September it is 3 percent.

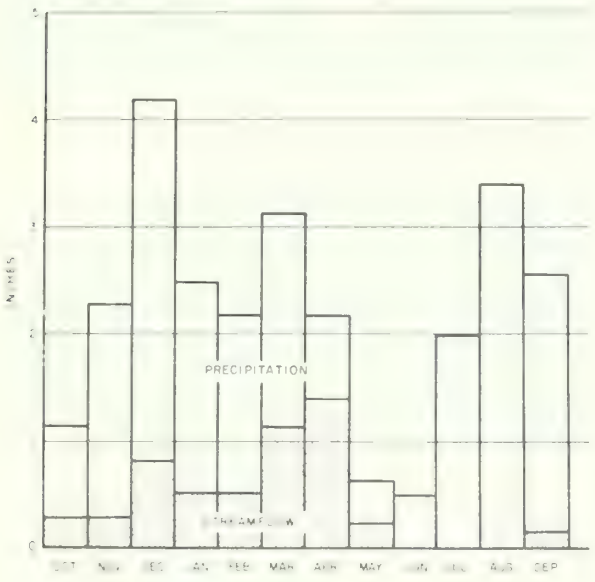

Figure 6.—Distribution of precipitation and streamflow on the Beaver Creek ponderosa pine watersheds.

Sediment.—Sediment yield data have been obtained by means of catchment basins and splitting devices installed on Watersheds 9, 10, 12, 14, 16, and 17. These installations (fig. 7) are described in detail by Brown et al. (1970). Suspended sediment concentrations have also been sampled intensively on all watersheds. Approximately 1,000 samples have been analyzed, and the results are to be reported in a later publication.

Mean annual sediment yields from untreated pine watersheds (26 station years) have varied from a trace (less than 0.005 ton per acre) to 6 tons per acre, with an average of 0.6 ton per acre over an 11-year period of record. This average, however, should not be used to characterize total yields from pine areas because it is influenced heavily by the 100-year storm of September 5, 1970. Excluding this extreme event, annual sediment yields have averaged only 0.02 ton per acre.

Except for the September 1970 storm, essentially all sediment has been produced during winter seasons. Winter sediment yields have ranged from a trace to 0.06 ton per acre with an average of 0.02 ton per acre.

Sediment yields from individual untreated watersheds have ranged from a trace to 11 tons per acre during the 11-year period of record. The 11 tons per acre were derived from Watershed 10 during the September 1970 storm which produced a peak streamflow discharge of 1,090 $ft^3/s/mi^2$ with an estimated recurrence interval of over 200 years.[5] This watershed was within or near the center of maximum 30-minute precipitation intensity and total storm precipitation, 3.0 inches per hour and 7.0 inches, respectively.

The only peak discharge recorded on Beaver Creek which exceeds the amount in this storm was from a 3-year-old clearcut on Watershed 12 which had a discharge of 1,200 $ft^3/s/mi^2$ and a sediment yield of 9 tons per acre. Clearcutting in this case appears responsible for the high peak discharge and resulting high sediment yield.

On untreated Watershed 10 the high streamflow was apparently due to the high precipitation intensities. Contributing further to the high sediment yield was the apparent accumulation of sediment available in its channels; during its 7-year period of record it had never produced more than 0.03 ton per acre. Therefore, potential sediment yields of at least 11 tons per acre may be realized from individual untreated pine watersheds with characteristics similar to those found on Beaver Creek.

[5]*Based on estimates made by the U.S. Geological Survey.*

Figure 7.—Installation for obtaining sediment yield data. Coarser sediments are caught in the basin above the dam, while suspended sediment is sampled continuously by a series of three splitters.

Water Quality

Quality of runoff water has been analyzed since 1969. Only occasional samples have been collected and sampling conditions have varied. Most samples were of runoff from a melting snowpack. An exception was a group of four samples from the September 5, 1970, storm. Samples were taken at the flumes, either dipped or with a DH-48 sampler.

Average values for key water quality characteristics on untreated pine watersheds are summarized as follows:

Ion	Concentration *Mg/l*
TDS	44
Ca	5.1
Na	1.9
PO_4	.16
NO_3	.16
Fe	.29

Electrical conductivity ranged from 38 to 65 μ mho/cm. Sodium was low, with SAR (sodium absorption ratio) below 0.2 on all samples. No one watershed produced water of consistently different quality than any other. Water from the pine watersheds met quality standards for drinking water, aquatic life, and irrigation (National Technical Advisory Committee, FWPCA 1968). Only iron approached the unacceptable level for drinking water.

Timber

A comprehensive description of the timber stands on Beaver Creek is essential to this presentation, because results of the treatments and predictions produced by the current models are most applicable to these kinds of forest stands.

The forest on Beaver Creek is composed of a mixture of ponderosa pine (*Pinus ponderosa* Laws.), Gambel oak (*Quercus gambelii* Nutt.), and alligator juniper (*Juniperus deppeana* Steud.) with a combined basal area of 115 ft^2/acre. Pine basal area averages 92 ft^2, Gambel oak 18 ft^2, and alligator juniper 5 ft^2. Volumes of typical untreated stands average 2,050 ft^3/acre overall, of which 1,775 ft^3 are pine (Myers 1973), 230 ft^3 Gambel oak (Gevorkiantz and Olsen 1955), and 45 ft^3 juniper (Howell and Lexen 1939). Average board-foot volume of ponderosa pine is 4,070 fbm/acre (Ffolliott et al. 1971) of which only 5 percent are in grade 3 saw logs or better. Average growth of pine stands is 40 ft^3 or 75 fbm/acre/year.

The number of trees per acre by size class (table 1) is important because it characterizes the typical stand. There is an excess of trees in the 2- through 10-inch and 26-inch plus classes, and a shortage of trees in the 14- through 24-inch classes. Average site index (height in feet at 100 years) is 60 (Meyer 1938).

Table 1.--Average number of trees per acre, by species and diameter class, on Beaver Creek watersheds 8-10 and 12-18

Diameter class *(Inches d.b.h.)*	Ponderosa pine	Gambel oak	Alligator juniper[1]	Quaking aspen	All species
			Number		
Reproduction	174.67	82.91	4.95		262.53
2	349.83	40.65	19.73	0.24	410.45
4	90.88	20.13	4.98	.03	116.02
6	51.09	12.66	1.05	.02	64.82
8	36.66	5.46	.38		42.50
10	23.66	3.73	.10		27.49
12	12.39	2.99	.12		15.50
14	6.31	1.76	.05		8.12
16	2.60	1.03	.12		3.75
18	2.02	.74	.09		2.85
20	1.32	.47	.07		1.86
22	1.21	.20	.04		1.45
24	.97	.11	.09		1.17
26	.70	.06	.07		.83
28	.52	.02	.07		.61
30	.28	.01	.05		.34
32	.13		.02		.15
34	.07		.03		.10
36	.03		.04		.07
38	.01		.04		.05
40	.01		.01		.02
42			.01		.01
44			.02		.02
46			.01		.01
48			.01		.01
50			.02		.02
Total[2]	580.69	90.02	27.22	.29	698.22
			Percent[2]		
	83.17	12.89	3.9	.04	100.00

[1]Includes all *Juniperus* species.
[2]Exclusive of reproduction.

The inventory system used on Beaver Creek went beyond the standard estimates of volume, basal area, and number of trees per acre, to include timber quality data describing basic stem characteristics and defect features that influence quantity and quality for most primary products (Barger and Ffolliott 1970). Further refinements allow levels of stocking (Ffolliott and Worley 1973) to be calculated, such as the percent of tne area stocked to 50 ft^2 basal area in trees 18 inches or larger. From these stocking

levels, timber stocking, recreation potential, or forage production can be determined (Ffolliott and Worley 1965).

The number of trees per acre and site index are used to initialize the timber simulation model described in a later section. Growth information will be used to validate model predictions. Basal area is the stand density parameter used in production functions because of its effects on other products such as runoff, sediment, and forage yields.

Range

Total herbage production in the pine type on Beaver Creek averages 198 pounds per acre annually for untreated conditions, consisting of 124 pounds of perennial grasses, 58 pounds of forbs and half-shrubs, and 16 pounds of shrubs. Following are the major herbaceous and shrubby species occurring under ponderosa pine stands (average pretreatment values for Watersheds 8, 9, 10, 12, 13, 14, and 17 based on 2 to 9 years of record):

Grasses and grasslike plants	Pounds per acre
Bluegrass, mutton (*Poa fendleriana*)	23
Dropseed, black (*Sporobolus interruptus*)	10
Grama, blue (*Bouteloua gracilis*)	23
Sedge (*Carex* spp.)	6
Squirreltail, bottlebrush (*Sitanion hystrix*)	46
Others	16
Forbs and half-shrubs	
Aster, showy (*Aster commutatus*)	3
Fleabane, spreading (*Erigeron divergens*)	4
Fleabane, trailing (*E. flagellaris*)	3
Goldeneye, showy (*Viguiera multiflora*)	3
Ragweed, western (*Ambrosia psilostachya*)	7
Snakeweed, broom (*Gutierrezia sarothrae*)	3
Wormwood (*Artemisia carruthii*)	3
Others	32
Shrubs	
Locust, New Mexican (*Robinia neomexicana*)	3
Oak, Gambel (*Quercus gambelii*)	13
Total	198

The range inventories on Beaver Creek originally involved only transect measurements of condition and trend, and plot measurements of production and utilization. Such measurements have been made periodically at 10 locations within Watersheds 7 through 14. At each location there is a cluster of ten 9.6-ft^2 herbage production and utilization plots and two 100-foot Parker 3-step transects. Herbage production is determined for each species by weight estimate and checked by clipping and weighing (Pechanec and Pickford 1937a). Forage utilization is determined by the ocular-estimate-by-plot method (Pechanec and Pickford 1937b). Ground cover and plant frequency are determined by the method of Parker (1954). The Parker transects aid in determining the ecological impact of the different treatments on plant composition and soil stability.

These conventional methods of range inventory, however, do not lend themselves to statistical sampling of large diverse areas. Thus it became necessary to measure herbage production at the timber inventory plot locations and to develop relationships between herbage production and more easily measured site characteristics of tree density and cutting history, soils, topography, forest floor characteristics, and composition and distribution of the forage. Some of these relationships are described by Clary (1964, 1969); Clary and Ffolliott (1966, 1969); Clary, Ffolliott, and Jameson (1968); Clary, Ffolliott, and Zander (1966); and Clary and Pearson (1969) (see later section on modeling). In addition, special studies have been initiated to characterize range response following unique treatments such as stripcutting and burning.

Wildlife

Big game use on Beaver Creek is measured in cooperation with the Arizona Game and Fish Department. Changes in the deer and elk use are estimated from counts of fecal droppings on plots superimposed on the timber inventory sample. Forage preferences of deer are determined by observing the plants eaten by tame deer under different treatment conditions. Production of preferred wildlife forage is determined by combining species yields and preference information. Observational studies have been conducted to determine the response of wild deer to different treatment situations. Hunter check stations and traffic counters have yielded information on the social and economic significance of the game resource.

Big game numbers have declined drastically on Beaver Creek throughout the period of the study, as they have in Arizona and the Southwest as a whole. Deer and elk populations calcu-

lated from Neff's 1959-60 data (Neff 1972) were 9 and 3 per section, respectively. During the period 1965 to date deer populations on untreated watersheds have been approximately 0.9 per section and elk 1.3 per section.

The forage plants on untreated areas that are most preferred by deer include, in order of preference (Neff 1974):

	Percent of deer diet
Gambel oak (*Quercus gambelii*)	38
Unidentified immature grasses	7
Ponderosa pine (*Pinus ponderosa*)	5
Redroot eriogonum (*Eriogonum racemosum*)	4
Geranium (*Geranium* spp.)	4
Clover (*Trifolium* spp.)	3
Milkvetch (*Astragalus recurvus*)	2
Mountainmahogany (*Cercocarpus* spp.)	2
Red-and-yellow pea (*Lotus wrightii*)	2
	67

Because of concern over environmental issues, the wildlife program on Beaver Creek was expanded in 1972 to include studies of birds, insects, carnivores, and desert cottontail, Abert's squirrel, and other forest rodents. The ultimate goal will be to describe the interactions between all major forest fauna and other ecosystem components under a variety of management conditions. The latter research is being conducted in cooperation with Northern Arizona University, the University of Arizona, and the Museum of Northern Arizona.

Esthetics

Much of the esthetic quality of forest lands can be attributed to the physiographic, climatic, and vegetative characteristics of the area. The ponderosa pine forests of Arizona are situated in an intermediate position between the State's widespread desert and woodland regions and its higher (but widely separated) montane forests of aspen and mixed conifers. Because this intermediate zone has a vigorous climate with relatively large seasonal variation, it provides a welcome visual relief for travelers and recreationists from other parts of the State. Its potential as an area of high scenic value was suggested by an 1858 military report:

> It is the most beautiful region I ever remember to have seen in any part of the world. A vast forest of gigantic pine, intersected frequently with open glades, sprinkled all over with mountains, meadows and wide savannahs, and covered with the richest grasses, was traversed by our party for many days (Lt. E.F. Beale, quoted by Cooper 1960).

The regional geology is such that the south-trending formations of the Colorado Plateau direct groundwater to feed several perennial streams which begin in an otherwise arid environment below the Mogollon Rim. Above the Rim on the plateau, a number of well-defined but in some cases ephemeral streams begin, which feed either the Little Colorado River or the Salt-Verde systems.

The Beaver Creek study area includes watersheds in both the woodland and the intermediate zones. Although the pine watersheds are above the Rim topographically, they nevertheless drain southward to the Salt-Verde River system and all of them contain ephemeral streams.

Litton (1968) developed the concept of characterizing landscapes or segments of landscapes by means of definable terms such as "panoramic," "feature," "enclosed," "focal," "canopied," "detail," and "ephemeral." Landscapes can be also described as either "macro," extending far into the distance, or "micro," where visibility is restricted to a matter of yards (U.S. Forest Service 1973).

Using this terminology we can briefly characterize the landscape of the ponderosa pine type on Beaver Creek, while considering at the same time the possible implications of several forest management practices.

These lands generally afford few, if any, **panoramic landscapes.** They are too flat, too covered with forest trees to provide vistas of the rolling distant countryside. Such a landscape could only be seen by ascending local promontories, and few locations provide this opportunity.

Stoneman Lake, a caldera, and Apache Maid Mountain provide outstanding **feature landscapes** in the study area. Distinct, visually important landscapes are relatively few on this uniform plateau.

Significant "macro" landscapes are provided at locations where one can look out across the Verde Valley — which suggests the opportunities for enhancing these views by carefully planned forest clearing along certain roadways.

The glades surrounded by forest referred to by Lt. Beale, may be what are now known locally as "cienegas" or "parks." Litton would call these **enclosed landscapes**: they are defined by their "wall" and "floor" characteristics. Land managers can create enclosed landscapes by cutting harmonious forest openings. **Focal landscapes,** on the other hand, can occur anywhere

that roads, landforms, vegetative patterns, or waterways lead the observer's eye to a point of convergence.

Canopied landscapes, characterized by immediate overhead trees, abound for the hiker in the ponderosa pine forest but are observed by the motorist only when he is travelling narrow, unimproved roads.

Detail landscapes, tied to minute segments of the immediate foreground, are an important consideration in making esthetic evaluations of forest treatments. It is the "micro" component of the landscape which includes such things as the bole of a mature ponderosa pine tree, lichen-covered rocks, or bracken fern on the forest floor. It can also include the slash, stumps, and soil disturbance that typify some cutover areas.

Ephemeral landscapes exist only for a brief period. Their creation and disappearance are generally caused by climatic or phenological events such as sunsets and autumnal coloration. The Gambel oaks, aspen, and occasional maples associated with the pine forests provide an abundance of fall colors which are widely appreciated in Arizona. Likewise the effect of man may be ephemeral, depending on the permanence of his impact.

Other concepts of landscapes quality dealing with "variety," "deviations," and "contrast" (U.S. Forest Service 1973) also have implications for forest treatments. Since they imply changes in forest cover, however, we will deal with them under treatment responses.

Many people feel that quality landscapes are characterized by a pleasing degree of variety, with the various components of the landscape appearing to be in harmony with each other. Harmony demands that variety be of a compatible size scale; also, it is important that small-scale variations should not be repeated indefinitely, nor should large-scale variations be easily recognized. These concepts are obviously quite subjective.

The overall landscape quality of this pine area, although pleasing, can be improved. It can also be damaged by inappropriate land management practices. Like other resources, the scenic resource requires sound investments guided by skillful management in order to attain its potential value, especially in view of the increasing and competitive demands being made on the forests of the Rim Country.

Treatment Tests

Seven treatments are presently being evaluated in the pine type on Beaver Creek. Two more are scheduled in 1974. With one exception, a wildfire, all treatments are on calibrated watersheds. All are timber overstory removal treatments except for grazing.

The earlier treatments were designed to increase streamflow, but were evaluated in multiple use terms. The two most recent treatments, on Watersheds 14 and 16, incorporated numerous features to enhance timber, wildlife, and esthetic values. The two treatments scheduled in 1974 are designed primarily to enhance wildlife (Watershed 10) and timber (Watershed 8). The early treatments have been described by Brown (1970, 1971) and O'Connell and Brown (1972).

Two basic kinds of timber overstory removal are considered: thinning and cleared openings. Different basal areas and spacing of openings are being tested to evaluate a range of treatment intensities. Clearing all the woody vegetation is being tested as the most severe level of treatment to determine maximum possible water yields.

With the recent shift of objectives toward development of multiple use management models, the treatments are now viewed as providing validation data for mathematical models that can be used to estimate treatment response for a wide range of conditions. These models will be discussed in a later section.

Description of Treatments

Thinning by group selection on Watershed 17 in 1969 (fig. 8).—Seventy-five percent of the initial 120 ft^2 basal area was removed by thinning, leaving evenaged groups with average basal areas of 30 ft^2/acre (basal areas are total, for all species). All Gambel oaks over 15 inches d.b.h. except den trees were removed, leaving 5 ft^2/acre of oak basal area; all alligator junipers were removed. The slash was windrowed. Theoretically, the treatment would be repeated every 20 years.

Stripcut for water yield on Watershed 9 in 1967-68 (fig. 9).—Thirty-two percent of the watershed was clearcut in uniform strips 60 feet wide, and slash was pushed to the center of cut strips and partially burned. Spacing between cut strips is 120 feet. Pretreatment basal area, all species, was 119 ft^2/acre; posttreatment was 81 ft^2. Cut strips will be allowed to restock naturally. The area between cut strips was not treated. The treatment is theoretically planned to be repeated every 40 years, so that in a rotation of 120 years the whole watershed would be cut.

Strip shelterwood cut on Watershed 14 in 1970-71 (fig. 10).—One-third of the watershed was cleared in irregular cut strips averaging 60 feet wide. Intervening leave strips which average 120 feet wide were thinned to 80 ft^2 basal area by a silvicultural cut favoring tree diameter classes that are in short supply on the Coconino National Forest. The original basal area of all species was 121 ft^2/acre; the post-treatment basal area was 60 ft^2 overall, yielding an overall reduction of 50 percent. Heavy concentrations of slash from leave strips were pushed into piles in the cut strips and burned. Pine seedlings were planted in the cut strips on better sites. Esthetic areas were preserved from any treatment, and Gambel oaks less than 15 inches d.b.h. were left in both cut and leave strips to benefit wildlife and esthetics. Trees will be thinned back to 80 ft^2/acre at 20-year intervals, and new strips will be cut at 40-year intervals.

Strip shelterwood cut on Watershed 16 in 1971-72.—Fifty percent of the watershed was cut in irregular strips averaging 60 feet wide. In the intervening leave strips, which also average 60 feet wide, the trees were thinned to 80 ft^2 basal area. Sixty-five percent of the basal area was removed overall. Gambel oak and slash were treated as in Watershed 14. Esthetic areas were preserved from any treatment. At 20-year

Figure 8.—In 1969, 75 percent of the basal area was removed on Watershed 17 in a heavy thinning treatment.

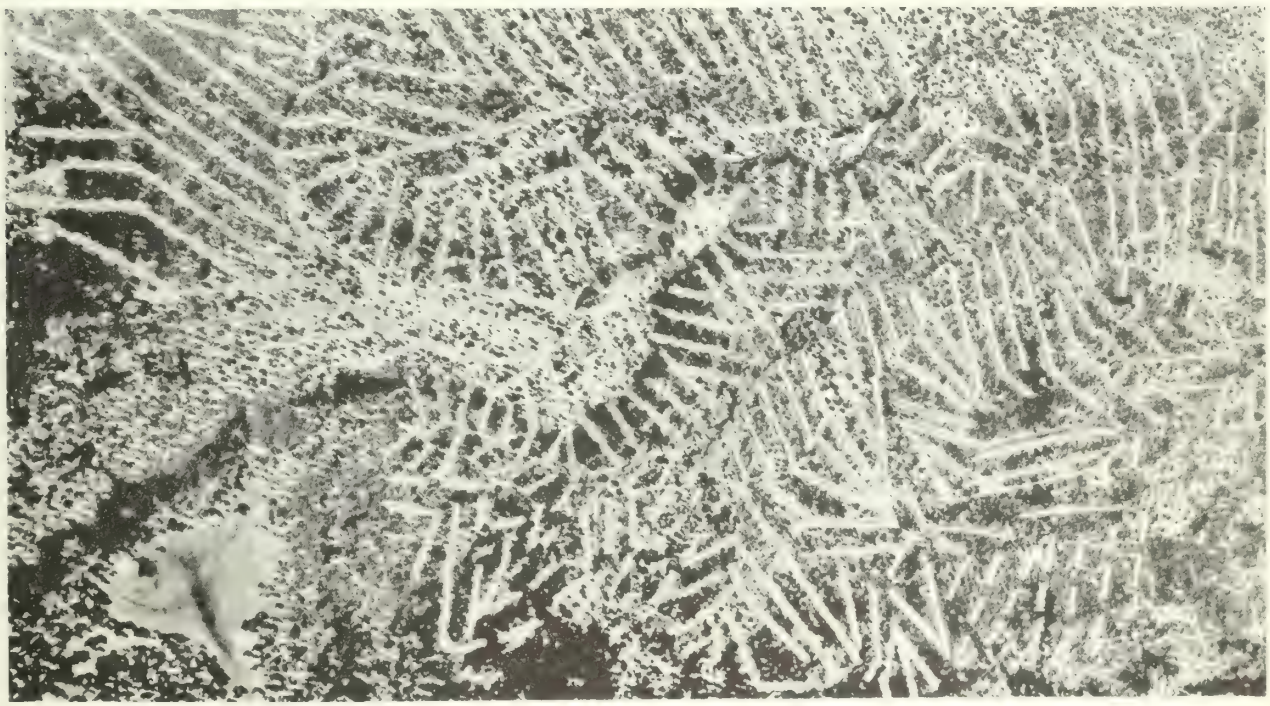

Figure 9.—One-third of Watershed 9 was cleared in 60-foot wide strips, with no treatment of the intervening areas. The strip width was chosen to maximize trapping and retention of snow. The strips were oriented to lead water directly into the streams.

intervals the stands will be thinned back to 80 ft^2/acre of basal area, and at 60-year intervals the alternate strips will be cut.

Total clearcut on Watershed 12 in 1966-67 (fig. 11).—This watershed was essentially removed from timber production. The slash was windrowed and oak sprouts were partially controlled with chemical sprays. While some natural restocking is taking place, it will be many years before any timber-oriented work will be done unless the area is planted. This treatment is not intended to have operational potential but rather is an analytical benchmark against which to compare less severe treatments.

Grazing on converted Watershed 11 (fig. 12).—Sixty percent of the perennial grass on the watershed has been utilized by cattle grazing in the spring and fall, starting in the fall of 1967. The watershed had been converted from pine to grass in 1958.

Wildfire of severe and moderate intensities in 1972.—The effects of wildfire are being studied on two small uncalibrated watersheds, one burned severely and the other moderately. The Rattle Burn fire occurred in the spring of 1972, 30 miles southwest of Flagstaff. Shortly afterwards three small watersheds were instrumented, two on the burn and one nearby for a control. Special emphasis in the evaluation of this treatment is being placed on wildlife effects, nutrient movement, and water infiltration into the soil.

Treatment Responses

Streamflow responses have been evaluated on six Watersheds: 12 — clearcut; 9 — one-third regular stripcut; 17— three-fourths thin; 14— one-third irregular stripcut and thin; 16— one-half irregular stripcut and thin; and 11— grazing. Total **sediment** yield has been evaluated only on Watersheds 12, 9, 17, 14, and 16. An unusually large storm in September 1970 provided an additional basis for evaluating flood response on Watersheds 12, 8, 17, and 11. Intensive suspended sediment sampling provides the only basis for evaluating sediment from the grazing treatment on Watershed 11. **Herbage** responses have been intensively evaluated on Watersheds 12, 9, and 11. Herbage production models, now under development, will be used later to predict responses to the other treatments.

Streamflow.—Responses of winter streamflow to the vegetative treatments on the pine watersheds are summarized in table 2. Mean winter streamflow for the untreated condition is based on variable periods of record, and has been adjusted by covariance to minimize uncontrolled variation due to climate and other factors not associated with treatment (Kovner 1956, Kovner and Evans 1954, Wilm 1943). This analysis is designed to detect treatment responses of greater than 15 percent at appropriate risk levels. Responses for individual years following treatment are determined by sub-

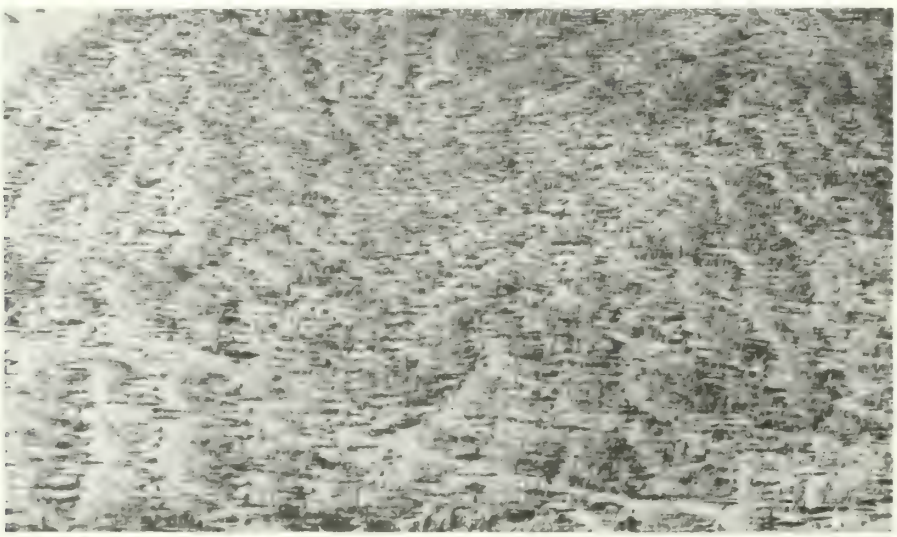

Figure 10.—One-third of Watershed 14 was cleared in 1971 in a pattern of irregular strips which vary in width from 30 to 90 feet. The intervening strips have been thinned to 80 ft^2 basal area to improve timber growth. The cut strips on better sites have been planted to assure continued timber production. Oak trees are left standing in the cut strips to enhance esthetic and wildlife values. Three especially attractive "esthetic areas" were not treated.

Figure 12.—A treatment started in 1967 on Watershed 11 is designed to determine whether more streamflow is produced under 60 percent grazing use than under no grazing.

Figure 11.— Aerial view of pine clearcut on Watershed 12. The slash was windrowed in a pattern to trap snow and expedite water movement into the streams.

Table 2.--Summary of effects of treatments on winter streamflow from the pine watersheds

Watershed, by treatment, and year treatment completed		Untreated mean winter streamflow[1]	Difference between actual and predicted streamflow by years following treatment[2]						Mean difference	Percent difference	Level of significance
			1st	2d	3d	4th	5th	6th			
Watershed 12--											
100% clearcut	1967	6.04	3.79	0.92	1.81	1.47	1.39	3.29	2.03	34	0.01
Watershed 9--											
32% clearcut in uniform strips	1968	6.70	1.98	.61	.34	.84	1.74		1.10	16	.05
Watershed 11--											
60% utilization of perennial grass	1967	3.16	.34	.24	.11	.29	-.20	.78	.26	8	([3])
Watershed 17--											
75% thin	1969	7.63	.85	1.45	1.51	2.93			1.68	22	.05
Watershed 14--											
33% pine clearcut in irregular strips, thinning between strips; 50% basal area removed overall	1970	4.71	.71	.70	1.61				1.01	21	.05
Watershed 16--											
50% clearcut in irregular strips, thinning between strips; 65% basal area removed overall	1972	5.45	5.60						5.60	103	.01

[1] Adjusted by covariance for years 1960-73 for watersheds 12, 9, 14; 1961-73, watershed 11; 1963-73, watersheds 16 and 17.

[2] Predicted streamflow is that which would be expected to occur in a given year had the watershed not been treated.

[3] Not significant at 0.05 level.

tracting the flow that would be predicted to occur, assuming pretreatment vegetative conditions, from the actual. Average treatment responses are expressed quantitatively in inches and as a percent of the pretreatment mean.

The largest response in winter streamflow was from an irregular stripcut and thinning treatment on Watershed 16 which removed 65 percent of the timber basal area. The response averaged 5.6 inches or 103 percent for the first year after treatment, and was significant at the 1 percent level. This very large response should be interpreted with caution. It is partially the combined result of the unusually wet 1973 winter and the large increase that is usual the first posttreatment year. The theory behind the irregular stripcut and thin treatment is that decreased water loss by transpiration and increased efficiency of runoff transport in the cut strips will increase water yield from the watershed. More efficient waterways for transporting surface runoff into the channels are believed to be formed by orienting cut strips perpendicular to the slopes and by reducing the soil water deficit through tree removal. More snow should also reach the ground in the cut strips due to reductions in interception losses and in redistribution of snow by the wind. The snowpack in the east-west oriented strips is partially shaded, thus reducing evaporation losses during the winter. This also produces more efficient runoff by delaying melt until the ambient temperature is relatively high.

The second largest response in winter streamflow came from the 100 percent clearcut on Watershed 12. The runoff increase averaged 2.0 inches per year or 34 percent over a 6-year period, and was significant at the 1 percent level. The increased water yield from this clearcut treatment is primarily due to a decrease in water loss by transpiration. By reducing the soil moisture deficit on the watershed, more runoff is realized from the melting snowpack. In addition, the windrowed slash traps snow and delays melt rates on the lee side. With delayed snowmelt, snow remains on the watershed until the ambient temperature rises high enough to melt the snow rapidly, and more surface runoff thereby reaches the channels. The efficiency of surface runoff transport is also increased because the windrows, which are directed downslope, shade the soil on their lee side. This reduces soil moisture loss and provides more efficient waterways for transporting surface runoff into the channels.

The third largest response resulted from the removal of 75 percent of the timber basal area by thinning on Watershed 17. The average increase was 1.7 inches per year or 22 percent for a 4-year period, and was significant at the 5 percent level. Again the response is apparently due largely to greater efficiency in surface runoff and reduced transpiration loss. The residual slash was piled into windrows and had an influence on the snowpack similar to that on the clearcut Watershed 12.

Watershed 14, which was stripcut and thinned, provided a 1.0 inch per year or 21 percent response over a 3-year period, significant at the 5 percent level. Watershed 14 can be expected to behave similarly to Watershed 16 but probably not as efficiently because only a total of 50 percent of the timber basal area was removed.

Watershed 9 had 32 percent of its timber removed in uniform downslope strips. Streamflow increase was 1.1 inches per year or 16 percent over a 5-year period, significant at the 5 percent level. Watershed 9 is expected to behave similarly to Watersheds 14 and 16. The vegetation treatment differs on Watershed 9 in that the cut strips are uniform in width, the leave strips were not thinned, and no oak trees were left in the cut strips.

Watershed 11, which has been grazed after conversion to a grass cover, shows only an 8 percent increase after a 6-year period. This increase is not statistically significant at the 5 percent level, and does not approach practical importance. It was theorized when this treatment was planned that grazing might reduce herbaceous plant growth and result in an increase in water yield due to reduced transpiration losses. It was also thought that compaction of the soil by the cattle might contribute to the efficiency of surface runoff. Plant growth has changed negligibly, however, (see table 5), and soil compaction apparently was not sufficient to produce an important increase in surface runoff.

A special commentary is in order regarding the unusually wet winter of 1972-73, and its effect on watershed treatment responses. The highest previously recorded winter precipitation for pine watersheds on Beaver Creek was in water year 1965, and ranged from 21 to 28 inches. The resulting runoff was also the previous high on record, ranging from 6.3 to 14.1 inches. In the winter of 1972-73 these watersheds received between 32 and 41 inches or an average of 1.5 times more precipitation than in 1965. Runoff was 11.1 to 27.8 inches or an average of 1.8 times more than the previous high. Responses to treatment during water year 1973 exceeded all but the first-year responses on Watersheds 9 and 12 (table 2).

Flood peak.—The major storm which struck Beaver Creek in September 1970 provided an opportunity to assess the effect of the pine

treatments on flood peaks.[6] Estimates of treatment effects are summarized in table 3. These responses were determined graphically, based on the relationship between peak discharge and 60-minute precipitation intensity (fig. 13). The assumption here is that the departures of a treated watershed from the untreated watershed relationship represent a treatment response. Table 3 also contains the estimated recurrence intervals for the observed peak discharges.

Peak discharge increased most — 750 $ft^3/s/mi^2$ — on Watershed 12. The second largest response was 400 $ft^3/s/mi^2$ from Watershed 11, which had been clearcut and seeded to grass in 1958, 12 years prior to the storm.

Responses which were apparently due to the complete or large reduction in timber and associated litter cover from Watersheds 11, 12, and 17 ranged from 350 to 750 $ft^3/s/mi^2$, or about twice the peak discharge expected from an untreated watershed with similar precipitation intensity. On the average, 92 percent of the timber basal area had been removed from these watersheds. They were subjected to 5.6 inches total rainfall with 1.1 inches maximum 60-minute intensity.

The recurrence interval for the flood runoff ranged between 100 and 200 years for the treated pine watersheds. This corresponds favorably with the recurrence interval of 100 years for 24-hour rainfall of 5.5 to 6.0 inches (U.S. Department of Commerce 1967).

Sediment.—Annual sediment yields from clearcut Watershed 12 have varied from 0.01 to 27 tons per acre since treatment. On stripcut Watershed 9, with a residual basal area of 81 ft^2/acre, they have varied from 0.01 to 1.3 tons per acre. On heavily thinned Watershed 17, with 30 ft^2 basal area, they have been from 0.03 to 0.32 ton per acre.

Watershed 11 does not have an installation to measure total sediment yield, but suspended sediment samples were collected periodically before and after the grazing treatment was imposed. Average suspended sediment concentra-

[6] *Baker, Malchus B., Jr., Harry E. Brown, and Norman E. Champagne, Jr. Hydrologic performance of the Beaver Creek watersheds during a 100-year storm. Paper presented at Amer. Geophys. Union meeting, San Francisco, Calif., 19 p. Dec. 1971.*

Table 3.--Summary of effects of treatments on flood peaks for the September 1970 storm on the pine watersheds (all discharges rounded to nearest 50 $ft^3/s/mi^2$)

Watershed, by treatment, and year treatment completed		Flood peak			Estimated recurrence interval[1]	Since treatment
		Estimated, untreated conditions	Actual	Estimated difference due to treatment		
		- - - $ft^3/s/mi^2$ - - -			- Years -	
Watershed 12-- 100% clearcut	1967	450	1,200	750	150-200	3
Watershed 9-- 32% clearcut in uniform strips	1968	500	600	[2]100	100-150	2
Watershed 11-- 60% utilization of perennial grass	1967	450	850	400	100-150	[3]12, (3)
Watershed 17-- 75% thin	1969	400	750	350	100-150	1
Watershed 14-- 33% pine clearcut in irregular strips, thinning between strips; 50% basal area removed overall	1970	450	550	[2]100	100-150	([4])

[1] Estimated recurrence intervals were determined by the U.S. Geological Survey, Tucson, Arizona, using regionalized peak discharge data from the Beaver Creek watersheds.
[2] Only a marginal response if indeed significant.
[3] Twelve years since clearcut and 3 years since grazing treatment imposed.
[4] Treatment 40 percent completed.

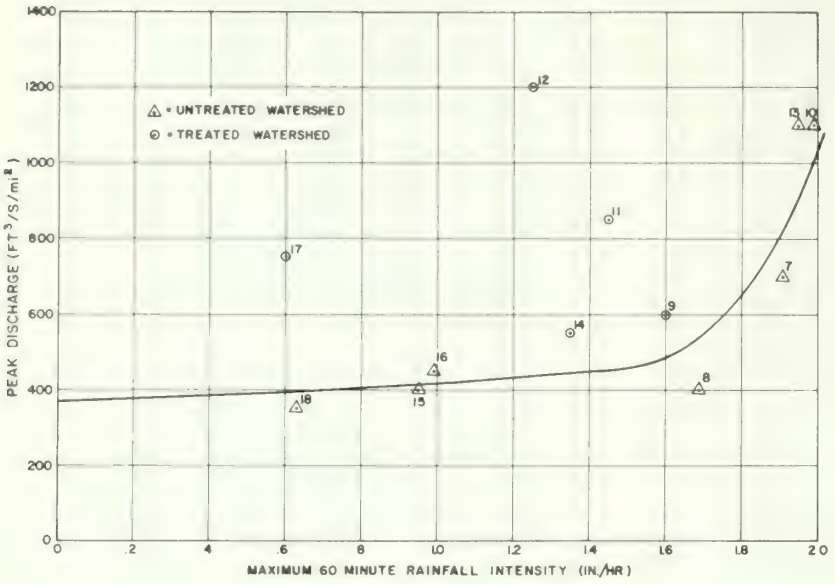

Figure 13.—

Flood peak response

determined by relationship

of peak discharge to maximum

60-minute rainfall intensity.

tion prior to grazing was 176 p/m (38 samples) and the average following treatment was 113 p/m (29 samples). The difference between these two averages is not significant at the 20 percent level.

The largest sediment yield, 27 tons per acre, was produced on Watershed 12 after it had just been clearcut. Because all slash had been pushed into windrows, nearly 100 percent of the surface soil was disturbed by the piling equipment. The entire treatment was completed in June 1967. On July 31, 1967, this watershed received 2.2 inches of precipitation with a maximum 30-minute intensity of 2.8 inches per hour. The resulting 2.1 inches of runoff overtopped the flume and washed out the sediment basin below it. The sediment yield of 27 tons per acre was estimated from measurements in the field and substantiated by measurements obtained from pre-and poststorm aerial photographs of the watershed.

From the sediment yield records obtained during the past 11 years on Beaver Creek, and from knowledge of the sediment losses resulting from various treatment intensities and storm frequencies, it appears that 27 tons per acre is approaching the maximum sediment loss potential from watersheds with similar characteristics in the ponderosa pine type.

It is difficult to develop a relationship to adequately predict sediment yields because of the limited amount of data. However, an initial attempt will be described in a later section, using maximum annual 30-minute precipitation intensity and timber basal area as independent variables.

Water quality.—TDS (total dissolved solids), which are indicative of overall water quality, were apparently not affected by treatments. Although the mean TDS from treated watersheds was nearly 5 milligrams per liter greater than from untreated watersheds, a difference of nearly 10 percent, analyses were not statistically conclusive.

Analysis of correlation between discharge in the flume at the time of sample collection and TDS in the samples from the pine watersheds yielded a coefficient of -0.44, not significant at the 5 percent level. Thus no clear relation is evident between rate of flow and quality of runoff water.

Samples from both treated and untreated watersheds met water quality standards for drinking water, fish and aquatic life, and unrestricted use for irrigation. Only iron approached an unacceptable level for drinking water. All samples had extremely low sodium absorption ratios. Electrical conductivity values of all pine watershed samples were 72 μ mho/cm or under.

Based on the classification of Durfor and Becker (1964, p. 27), water samples from the pine watersheds were soft (0 to 60 mg/l of $CaCO_3$).

Suspended sediment was determined on samples taken concurrently with those reported here. Correlation analysis showed no consistent relation between suspended sediment and TDS of the waters.

Timber.—No direct measures of timber responses have been possible because the watersheds have not had time to respond to the treat-

ments. Thus the only means available for determining response has been the simulation model described in a later section. This model uses Beaver Creek inventory data consisting of an average stand table for each soil type. Estimates for rate of natural regeneration and mortality are determined for each soil type. Functions are computed for growth and the effect of density on growth.

All of the treatments were simulated for a full rotation, and the total products harvested are estimated in table 4. Past management was also simulated for each watershed, and these results are also included in the table. Past management consisted of harvest cuts every 40 years to remove overmature and dying trees, salvageable snags, and some mature and older blackjacks. No timber stand improvement work was done, and no pulpwood was sold.

Volumes removed in the initial treatment cuts were omitted from the simulation analysis in order to best describe the long-term effects of the treatments without the bias introduced by the initial cut. Consequently the cleared Watersheds, 11 and 12, produce no timber under the alternative treatment prescriptions, and a net loss in timber products is shown. Every 40 years, one-third of Watershed 9 would be cleared, resulting in young stands capable of rapid cubic-foot growth until tree growth diminishes due to increasing stand density. This pattern causes rapid growth on young trees but slow growth in older saw log-sized stands, with a net gain in cubic-foot volume but net loss in board-foot volume. While one-third of Watershed 14 is cut every 40 years, timber production is higher than under past management for two reasons: the cut strips are planted, thus keeping the watershed under full production, and the leave strips are thinned for stand improvement and growth. Estimates for Watershed 17 indicate that it may be possible to maintain good volume production at very low stocking levels by intensive management.

Range.—With the exception of the grazing treatment on Watershed 11, the Beaver Creek treatments consist of reductions of timber

Table 4.--Predicted treatment effects on wood products sold from the pine watersheds for a 120-yr rotation

Watershed, by treatment, and year treatment completed		Volume per acre					
		Under past management[1]		Under alternative-treatment prescriptions[2]		Difference	
		ft^3	*fbm*	ft^3	*fbm*	ft^3	*fbm*
Watershed 12--							
100% clearcut	1967	800	4,200	0	0	-800	-4,200
Watershed 9--							
32% clearcut in uniform strips	1968	1,500	7,500	2,000	6,300	500	-1,200
Watershed 11--							
60% utilization of perennial grass	1967	500	2,800	0	0	-500	-2,800
Watershed 17--							
75% thin	1969	1,400	6,800	3,900	11,700	2,500	4,900
Watershed 14--							
33% pine clearcut in irregular strips, thinning between strips; 50% basal area removed overall	1970	1,100	5,500	3,300	11,200	2,200	5,700

[1]Past management consisted of harvest cuts every 40 years to remove overmature and dying trees, salvageable snags, and some mature and older blackjacks.
[2]Volumes removed in the initial cut were omitted in order to best describe the long-term effects of the treatment without the bias introduced by the initial cut.

overstory by differing degrees and in different patterns. Such reductions invariably result in an increase in the production of herbaceous plants, and often of shrubby understory plants as well. These responses increase with increasing degrees of overstory removal.

On Watershed 12, all timber overstory was removed. The native herbaceous and shrubby plants increased an average of 504 pounds per acre for the five posttreatment years (table 5). This increase in understory plant yields means greater livestock and big-game carrying capacities. If the cattle carrying capacities are based on: (1) grass production only, (2) assumption that 750 pounds of allowable forage disappearance represents one animal-unit of carrying capacity, and (3) 40 percent maximum allowable use, then the carrying capacity for cattle would have increased from 0.11 animal-unit month per acre to 0.23 AUM per acre as a result of treatment.

Watershed 9 was stripcut with no thinning of the leave strips, thus herbage response can only be expected on one-third of the area. By the second year after treatment the average increase in production of understory plants was statistically significant, but not yet of sufficient magnitude to have practical importance. The sampling of the stripcut treatment was relatively intense, but limited to specific combinations of slope, aspect, and soils. Thus the results do not represent a watershed mean.

The treatment of Watershed 11 consisted of spring and fall grazing by livestock, with the

Table 5.--Summary of effects of treatments on herbaceous and shrubby plant production for the pine watersheds on Beaver Creek

Watershed, by treatment, and year treatment completed		Plant group	Production, untreated conditions	Difference between actual and predicted production by years following treatment[1]						Statistical significance of average change[2]
				1st	2d	3d	4th	5th	Average	
			Pounds per acre							
Watershed 12--		Grasses	200	176	252	174	262	319	237	0.01
100% clearcut	1967	Forbs,half-shrubs	109	313	168	156	211	382	246	.02
		Shrubs	20	-20	1	11	45	66	21	NS[3]
Watershed 9[4]--		Grasses	30	12	10	--	--	--	11	.05
32% clearcut in		Forbs,half-shrubs	26	49	32	--	--	--	40	.01
uniform strips	1968	Shrubs	11	3	12	--	--	--	8	NS
Watershed 11--		Grasses	390	-118	-1	215	303	-12	77	NS
60% utilization of		Forbs,half-shrubs	339	-131	-104	-181	-61	-5	-96	.10
perennial grass	1967	Shrubs	0	1	2	0	1	0	1	NS
Watershed 17--		Grasses	86	--	--	--	--	--	--	--
75% thin	1969	Forbs,half-shrubs	45	--	--	--	--	--	--	--
		Shrubs	15	--	--	--	--	--	--	--
Watershed 14--		Grasses	137	--	--	--	--	--	--	--
33% pine clearcut in		Forbs,half-shrubs	86	--	--	--	--	--	--	--
irregular strips,		Shrubs	2	--	--	--	--	--	--	--
thinning between strips; 50% basal area removed overall	1970									

[1]Predicted production is an estimate of production that would be expected assuming the watershed had not been treated.

[2]Different sample designs and sampling intensities were used on the different watersheds; therefore, the reliabilities of the estimates differ.

[3]In 1968 and 1969, attempts were made to control Gambel oak sprouts with chemicals. The original treatment plus followup chemical application suppressed shrub (browse) production for several years. Since that time, Gambel oak sprout production has been steadily increasing. Additional sampling has indicated that oak sprout production has increased three to five times since treatment.

[4]Sampling was limited to sites exceeding 10 percent slope. These sites have greater timber densities and therefore low initial herbage production.

intent of removing one-half of the standing crop of perennial grasses during **each** grazing period. The proportion of the total perennial grass production removed yearly was 60 percent for the first 4 years of treatment, but dropped considerably the fifth year. This treatment caused no significant change in the production of grasses, but did apparently reduce the production of forbs. If we again base the carrying capacity for cattle upon the grasses alone, we would conclude that there has been no change in carrying capacity as a result of this treatment.

The understory plant responses on Watersheds 17 (3/4 thin) and 14 (stripcut plus thin) have not been directly sampled. It appears that after several posttreatment years these watersheds are producing about 100 pounds of additional herbage per acre, about one-half being grass. The dry years since treatment have obviously slowed the plant responses. Therefore, additional recovery time is needed before livestock carrying capacity will increase meaningfully.

In evaluating the effect of a treatment on livestock carrying capacity, we must consider whether the animals can or will take advantage of the increased forage yields. In the case of Watershed 12 the topography is relatively gentle, abundant water is nearby, and the cattle have demonstrated that they will distribute themselves over the watershed. Here we can conclude that the apparent increase in carrying capacity is realistic. On other areas such as Watershed 9, any increase in apparent carrying capacity will have to be tempered by the knowledge that livestock will probably spend little time on the steeper areas.

Wildlife.—The impact of watershed treatments upon wildlife values has been measured in two ways: (1) production of forage plants preferred by deer, and (2) big-game fecal droppings as an indirect index of animal use.

We do not know what a given increase in preferred plants means in terms of big-game carrying capacity, but an increase in the forage supply should be beneficial if cover requirements can still be met (Reynolds 1969). Big-game on Beaver Creek are known to prefer areas with better-than-average forage supplies (Clary and Larson 1971). The overstory reduction treatments applied to Watersheds 12 and 9 resulted in increased production of the preferred deer forage plants (table 6). The livestock grazing treatment on Watershed 11, on the other hand, reduced preferred plants.

The response of deer and elk to the treatments, as indexed by fecal droppings, roughly parallels the production of preferred forage plants. On Watershed 12 with the highest increase in preferred plants, deer use increased noticeably (table 7). Big-game use changed little on Watershed 9, which showed only a small increase in preferred plants. On Watershed 11 where production of preferred plants has been severely depressed, deer use remains low, while elk use has plummeted. On the other hand both deer and elk appear to be responding to the treatment of Watershed 17, even though there does not appear to be a large increase in herbage yields.

In general, opening the ponderosa pine canopy to enhance the understory forage supply improves deer and elk habitat (Neff 1972). It is still not possible, however, to predict the exact game response to any particular treatment.

The question of quantifying wildlife cover is a difficult one. Most wildlife biologists and wildlife managers avoid attempting to quantify cover requirements. Clearcutting Watershed 12 (455 acres) was expected by some to create a wasteland, from a deer standpoint. In fact, however, deer use of this watershed is several times higher than before treatment. The deer are apparently attracted by the abundant forage supply, while the slash windrows and Gambel oak sprouts provide sufficient cover. A critical evaluation of the effect of these treatments on wildlife cover requires additional understanding of the specific requirements of individual species.

Preliminary predictive models based on pellet counts were developed from several different studies. The graphs (fig. 14) are presented as an initial basis for evaluating the impact of a given treatment on deer use. The three different situations illustrated describe the relation of deer use to basal area.

The shape of relationship A applies to cleared forest openings smaller than 40 acres where the lack of cover does not inhibit deer use (Reynolds 1969). On these small areas, average big-game use will likely be proportional to forage supply (Reynolds 1962; Patton 1969) — highest at low timber basal areas.

Relationship B applies to areas 40 to 500 acres in size, surrounded by forest. Under these circumstances deer use peaked on a heavily thinned watershed of 300 acres where there was a moderate increase in forage and some remaining tree and slash cover (Neff 1973). The shape of relationship C is applicable to broad, uniformly forested areas (Reynolds 1969) where both cover and forage are provided on the same site.

Future intensive land management will undoubtedly be based on diversified sites, habitat types, and land response units, resulting in a mosaic of treatment patterns. Under these cir-

Table 6.--Summary of effects of treatments on forage plants preferred by deer in the pine type on Beaver Creek

Watershed, by treatment, and year treatment completed		Deer forage production, untreated conditions	Difference between actual and predicted production by years following treatment[1]						Statistical significance of average change[2]
			1st	2d	3d	4th	5th	Average	
		Pounds per acre							
Watershed 12--100% clearcut	1967	69	233	75	47	86	166	121	0.05
Watershed 9--32% clearcut in uniform strips	1968	16	21	13	--	--	--	17	.01
Watershed 11--60% utilization of perennial grass	1967	190	-166	-63	-87	-80	-46	-88	.10
Watershed 17--75% thin	1969	30	--	--	--	--	--	--	--
Watershed 14--33% pine clearcut in irregular strips, thinning between strips; 50% basal area removed overall	1970	37	--	--	--	--	--	--	--

[1]Predicted production is an estimate of production that would be expected, assuming the watershed had not been treated.

[2]Different sample designs and sampling intensities were used on the different watersheds; therefore, the reliability of the estimates differ.

cumstances, areas of uniform treatment will be limited to several hundred acres in size, thus making relationship B most applicable.

Esthetics.—To evaluate esthetic response of the Beaver Creek treatments we have utilized existing criteria from Agriculture Handbook 434 (U.S. Forest Service 1973) as well as current studies by Boster and Daniel (1972).

As indicated in a previous section, the "enclosed," "detail," and "ephemeral" segments of the landscape are particularly susceptible to change by forest treatments. These changes may be in terms of "variety," "deviations," or "contrast," and will result in changed forms, colors, or textures of the landscape.

Consider first the effects of the several land treatments on "variety." From the standpoint of landscape quality, some variety is desirable, but it is less obvious just how much variety is enough.

There is a point at which variety, increasing from zero, becomes visually pleasant or acceptable. As variety continues to increase, it approaches the point where it is no longer pleasant (it may decrease to zero again). In the sketches from the Agriculture Handbook (fig. 15), A and G tend to be the least interesting. The intermediate stages might prove to be the most enjoyable. Although not everyone would rate each sketch the same, most would pick the sketches in the middle range as most interesting and C or E, where the proportions are not equal, are likely to be preferred. Although a precise proportion cannot be determined, we can approximate the range on the variety scale at which visual acceptability is reached.

Figure 15 provides a basis for evaluating changes in variety brought about by several of the Beaver Creek treatments. We might infer that neither the untreated nor the clearcut areas provide desirable variety. The strip shelterwood cut on Watershed 14 would have the highest rank of the treatments. The severe thinning and severe shelterwood treatments on Watersheds 17 and 16 would have intermediate vari-

Table 7.--Summary of effects of treatments on deer and elk pellet group densities in the pine type on Beaver Creek[1]

Watershed, by treatment, and year treatment completed			Pellet group density, untreated conditions	Difference between actual and predicted pellet group densities by years following treatment[2]						Evaluation[3]
				1st	2d	3d	4th	5th	Average	
			- - - - *Pellet group per acre per month* - - - -							
Watershed 12--		Deer	0.4	1.2	1.3	1.6	0	1.6	1.1	Meaningful
100% clearcut	1967	Elk	1.0	-.6	-.6	-.2	([4])	.2	-.2	Not meaningful
Watershed 9--		Deer	.5	-.1	.9	.2	-.1	--	.2	Not meaningful
32% clearcut in uniform strips	1968	Elk	1.2	-1.0	-.6	-.8	1.2	--	-.3	Not meaningful
Watershed 11--		Deer	1.2	-.6	-.6	-1.0	-.8	-1.1	-.8	Not meaningful
60% utilization of perennial grass	1967	Elk	11.8	-8.6	-10.4	-8.7	-10.6	-10.8	-9.8	Meaningful
Watershed 17--		Deer	.8	.2	3.6	1.9	--	--	1.9	Meaningful
75% thin	1969	Elk	1.0	.3	6.3	4.3	--	--	3.6	Meaningful
Watershed 14--		Deer	.6	1.5	--	--	--	--	1.5	?
33% pine clearcut in irregular strips, thinning between strips; 50% basal area removed overall	1970	Elk	.4	.6	--	--	--	--	.6	?

[1]Adapted from: Neff, Don J. Effect of watershed treatment on deer and elk use. Job Progr. Rep. Proj. W78-16, Work Plan 4, Job 5. 1973.
[2]Predicted production is an estimate of production that would be expected assuming the watershed had not been treated.
[3]Evaluation of the treatment effect based on the judgment of the Arizona Game and Fish Department Biologist.
[4]Trace.

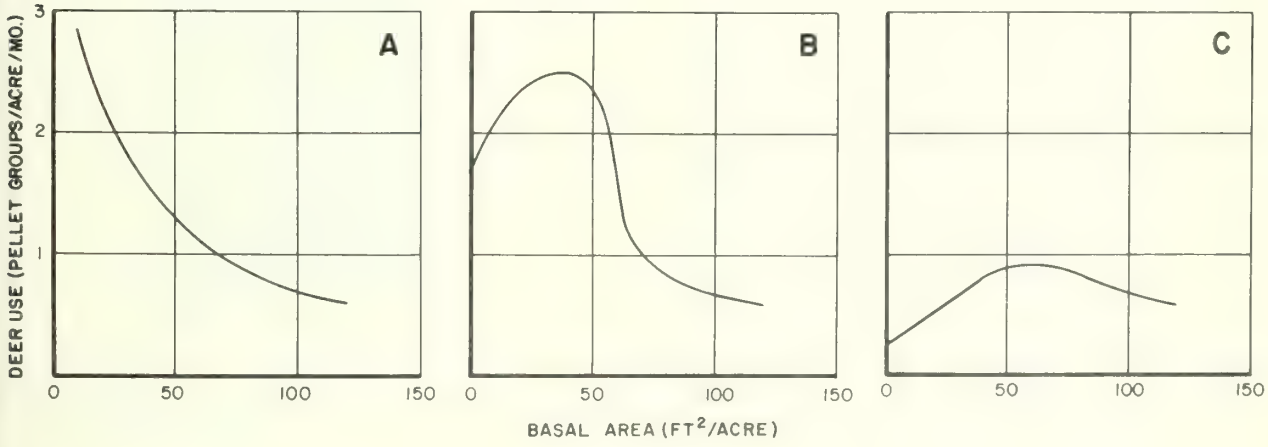

Figure 14.—Relationships of deer use to timber basal area: **A,** Areas of < 40 acres surrounded by forest cover of ≥ 100 ft.²/acre of basal area; **B,** Areas of 40 to 500 acres surrounded by forest cover of ≥ 100 ft.²/acre of basal area; **C,** Areas of uniform timber basal area.

ety rankings. If we related the sketches to basal area, it would appear that the intermediate basal area, 50 to 80 ft^2/acre, would have the highest variety ranking, especially if the residual stand is arranged in groups of trees.

The Handbook suggests that the intermediate sketches in fig. 16, (C and D) provide the more desirable degrees of variety. There are definite analogies in the uniform stripcut treatment on Watershed 9 (Sketch A) and the irregular shelterwood stripcut on Watershed 14 (Sketch D). The Watershed 14 treatment scores well in variety except where the strips appear too repetitive. The uniform stripcut on Watershed 9 is much less desirable.

Treatments that create unnatural-appearing deviations from the surrounding landscape are a distinct esthetic detraction. Watershed 12, which was clearcut, is in this category since it is essentially a single large opening covered with parallel windrows of slash. An irregular pattern of forest openings which borrow form, line, color and texture from the surrounding landscape would be preferable.

The ephemeral quality of the landscape can be enhanced by increasing the proportion of Gambel oaks and aspen in forest stands. Gambel oak has been retained on Watersheds 14, 17, and 16 primarily for its wildlife values, with the added result that fall colors are substantially enhanced.

Esthetics are being measured on ponderosa pine areas of the Coconino National Forest and elsewhere by means of an extension of the TSD (theory of signal detection) to evaluate viewer preference for alternative land treatments. The TSD model appears to have considerable promise for this type of evaluation (Boster and Daniel 1972; Boster 1973; Daniel et al. 1973).

TSD methodology was designed principally to distinguish between the two components of perceptual judgment: actual perception and the observers' standards. As noted in Daniel et al. (1973), it was further developed in response to a need to measure image quality when complex photographic displays are subjected to information retrieval or enhancement processes. The Forest Service is attempting to use TSD to answer two questions related to forest management: (1) can observers discriminate reliably among various vegetative treatments, and (2) do observers make differential esthetic responses to the various treatments? Ultimately the TSD approach permits the quantification of the esthetic judgments on a cardinal (or interval) scale rather than on merely an ordinal (ranking) scale.

During its developmental stage this evaluation technique was tested extensively with selected experimental watershed treatments.

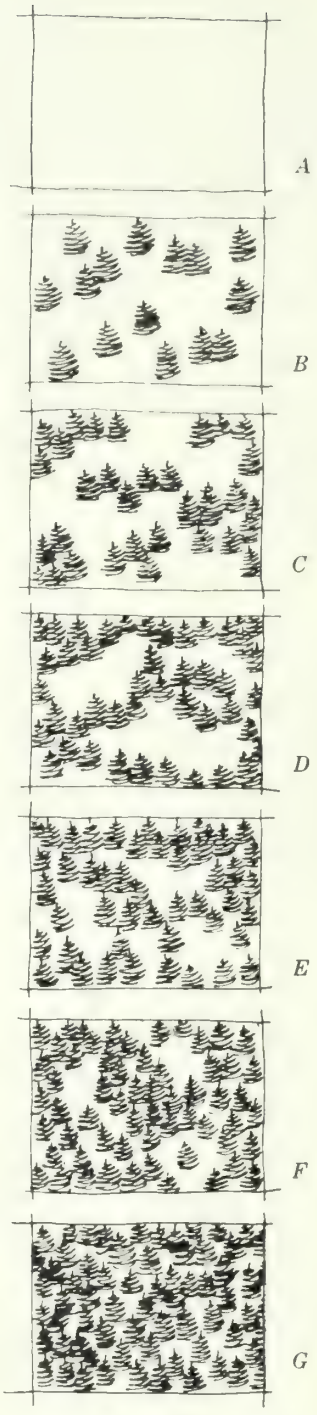

Figure 15.—Degrees of variety in a forest landscape (from U.S. Forest Service 1973).

After sufficient validity and reliability testing, a different set of areas was selected representing a wide array of feasible management options. Numerous definable groups of both forest

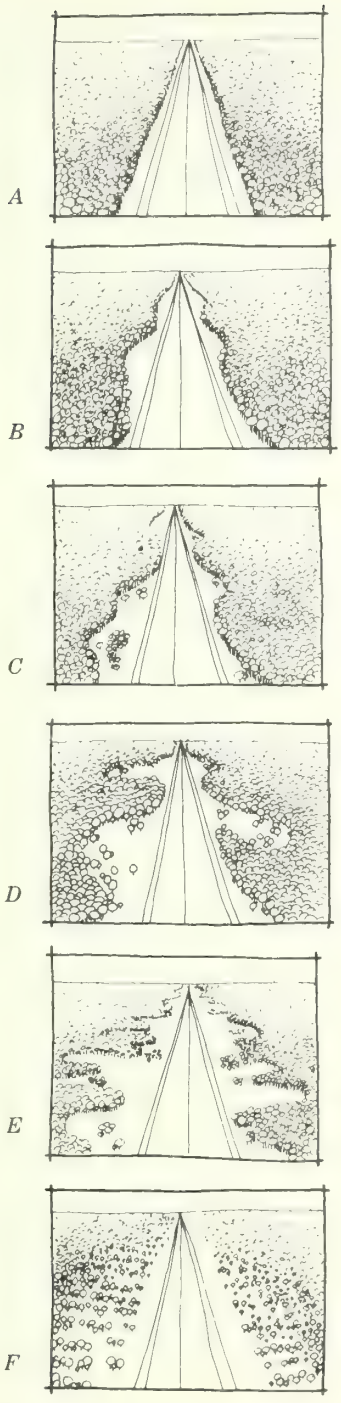

Figure 16.—Degrees of variety in the forest landscape along a road or other cut strip (from U.S. Forest Service 1973).

users and nonusers are now being questioned about their preferences for these alternative management practices:

Management practice	Area Description
Uncut[7]	Woods Canyon Decision Area
Irregular stripcut	Watershed 14
Heavy thin	Watershed 17, 30 ft^2/acre basal area
Moderate thin	Wild Bill Pasture, 60 ft^2/acre basal area
Recent management	'69 NFS "Horse Lake" sale area
Intensive management	'72 NFS "Fred Hought Ridge" sale area (a silvicultural prescription)

One of the most critical esthetic considerations concerns how cutting changes scenic quality. There is general agreement that scenic quality drops markedly immediately following harvest, then increases as vegetation recovers and logging scars heal. The main question is, How much recovery can we expect? Related questions concern whether the pretreatment scenic quality (A, fig. 17) will be reached or exceeded (curves a′ and a, fig. 17) and how much time will be required (x years in fig. 17). Ans-

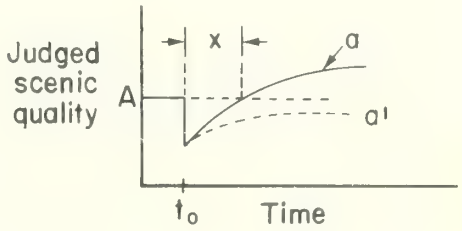

Figure 17.—Esthetic recovery of an area harvested in year t_o. See text for explanation of symbols.

wers to these questions are being sought by Boster and Daniel for several recently treated areas. The "recovery" of Watersheds 9, 14, and 17, plus that of a recently logged area that was lightly cut (Milk Ranch Point), have been followed for several years. These answers can be expected to go a long way toward filling an important void in forest management, providing scientific justification for various management options as they relate to scenic quality.

Boster and Daniel have conducted an extensive analysis to identify those factors which consistently increase or decrease viewer satisfaction. This analysis has resulted in a rather

[7]*The "uncut" area that, although lightly cutover, could lend itself to any of the five subsequent management practices.*

small list of significant factors. It has also fostered development of a management tool that will enable landscape architects and others to predict scenic quality solely from viewer judgments of landscape features. The factors used must be periodically updated because people's tastes and preferences change over time.

Landscape architects in Region 3 are being asked to scale representative slides with those factors found to best predict judged scenic quality. Based on their scaling, simple regression equations will be derived with scenic quality as the dependent variable and a small number of identifiable landscape features as the dependent variables. These equations will be usable by the landscape architects. The next step will be to predict judgments of scenic quality from preharvest prescriptions and sketches of proposed treatments (or from photos of existing stands typical of the proposed harvest prescription).

The relation between most of the factors that affect a viewer's satisfaction and the scenic value estimator statistic shows good agreement with theory. For example, variety and diversity (as represented by "tree density" and "average tree diameter") were found to be important factors. Also, scenes lacking harmony with the characteristic landscape (those having large amounts of down wood or slash, for example) have low preference ratings. Very open or very dense forest stands likewise were less preferred than stands with intermediate basal area levels. Figure 21 (page 30) illustrates this latter relationship, with esthetic preference plotted as a function of timber basal area. These and other preliminary relationships are being quantified for use in a model that will predict esthetic preference on the basis of a wide variety of pertinent variables.

Treatment Costs

Since treatment costs are covered in detail in another paper (Turner and Larson 1974), only a brief summary of costs will be presented here. Turner and Larson have developed regression models which predict thinning and piling costs as a function of the degree of timber basal area removed. Thinning costs are related to basal area removed noncommercially, while piling costs are related to total basal area removals including commercial logging. The costs are predicted in terms of dollars, and of man and equipment hour requirements per acre, so that wages and rates can be updated for any situation.

Sensitivity analyses indicate that these piling costs are representative for all but the most extreme conditions of slope steepness likely to be encountered in the Southwest. If the thinning operation involves removal of trees larger than 8 inches in diameter, cost variability may be greater than that accounted for by the thinning model.

By basing estimates on thinning and piling operations, which account for about 90 percent of the total costs, we can eliminate variation due to miscellaneous lesser jobs such as travel which varies between watersheds.

A general model applicable to both experimental and forest operations was obtained by relating costs to basal area removed. The cost to remove noncommercial trees was \$0.79 per ft^2 of basal area, while the piling cost was \$0.28 for each ft^2 of commercial and noncommercial basal area removed.

These costs are based on initial treatments. Estimates of total costs require projections to include subsequent precommercial thinnings and harvests throughout a complete rotation. Because treatments with high initial costs may have lower costs at future cuts, evaluation of a treatment alternative on the basis of initial costs could be very misleading unless future product flows and costs are accounted for and discounted back to present. This procedure can be handled internally by a multiple use allocation model which considers costs and yields at appropriate intervals throughout the planning horizon (Turner 1974).

Preliminary Models for Predicting Resource Responses in the Ponderosa Pine Type

A long-range aim of the Forest Service research program in Arizona is to provide an array of analytical procedures (models) for predicting the following responses to management activities:

1. Terrestrial/biotic responses (timber, range, and wildlife).
2. Hydrologic responses (water yield, quality, and timing, erosion, and sedimentation).
3. Stream and lake/biotic responses (fish habitat and production).
4. Natural beauty and recreation responses (esthetic value and recreation potential).
5. Fire responses (fire size and rate of spread).

Response data from such models will provide input to allocation and scheduling models, which can be used to allocate uses and activities to areas of land in a planning unit and to schedule activities on all planning units in a forest or region.

Physical models are already available for predicting some of these responses on ponderosa pine forest lands. A continuing effort

will be made to determine the suitability of these models and to utilize them to the extent possible in building an overall system of mutually compatible models suitable for use in planning and managing forest and related lands in the Southwest. This overall system of models will eventually be expected to produce all of the response information listed above.

Of the existing water yield models available, the Stanford Watershed Model (Crawford and Linsley 1966) is not suited for application on small watersheds. Because the USDA model (Holtan and Lopez 1971) is not capable of accounting for snowmelt, it is not applicable to areas such as the ponderosa pine type where a majority of runoff is derived from a melting snowpack. Water Yield I (U.S. Forest Service 1972) may be applicable to the Beaver Creek area but is not yet available for testing. Leaf and Brink's (1973) hydrologic model will be tested once it has been modified to function in areas with shallow or intermittent snowpacks. Testing of the BURP model (U.S. Forest Service 1968) is also being planned. Such testing work has been delayed, however, pending completion of an overall problem analysis concerning the development of models needed to provide management information for the Southwest forest ecosystems.

Meanwhile, preliminary models can be used to provide some initial arrays of response data. Two water yield models have undergone preliminary testing on Beaver Creek: Baker and Kovner's regression model, and Rogers' system theoretic model.

Baker-Kovner Streamflow Regression Model

First attempts at modeling streamflow on Beaver Creek have used a regression approach. A multiple regression to predict annual streamflow was developed from 148 observations from 12 watersheds in the pine type. Variables initially considered included precipitation, insolation, soil, geology, and timber density.

The objective was to formulate a model that was in accord with physical concepts influencing the hydrologic regime on the watersheds. Only parameters which logically influenced the water balance were considered. Relationships between parameters were also analyzed to determine if they were independent, linear, or curvilinear.

The initial model was a linear multiple regression which contained six variables. This equation was cumbersome, and examination showed that not all variables were independent. It also became apparent that the relationship was nonlinear. A following modification of the regression included winter precipitation, potential insolation, and timber density. It too was nonlinear.

Since 93 percent of the runoff on Beaver Creek occurs in the winter, winter precipitation was found to correlate best with annual streamflow. The potential insolation variable being used is a percentage of the potential insolation falling on a surface normal to incoming radiation (Fons et al. 1960). At present this variable has been indexed by using the present normal insolation occurring at 1200 hours on February 23. This particular date was selected because much of the snowmelt on Beaver Creek occurs around this time. The insolation variable may be improved in the future by using average annual or winter insolation values for the various watersheds.

Although the relationships developed with the basic data from the Beaver Creek watersheds between streamflow, winter precipitation, and insolation are linear, the expected relationship between vegetation and streamflow is S-shaped because of known upper and lower limits. Timber density parameters considered were number of trees, basal area, and cubic-foot volume per acre. Of these, basal area and cubic-foot volume appear to be most useful.

There is obviously interaction between precipitation, insolation, and timber density. Two interaction terms used in the regression are between winter precipitation-basal area and between winter precipitation-insolation. The form of the regression which has been developed is:

$$\hat{Y} = -5.72 + 0.83X_1 + 0.42X_2 - 0.24X_2X_1^{0.92} - 0.007X_1^2\left[1 - \exp - (X_3 / 45)\right]^3$$

$$R^2 = 0.69$$

$\hat{Y}$ = Annual streamflow in inches
X_1 = Winter precipitation in inches
X_2 = Insolation as a decimal fraction
X_3 = Timber basal area in ft^2/acre

The observational data for such a model is limited because there are only 12 watersheds. On Beaver Creek, winter precipitation has ranged from 8 to 28 inches, insolation from 0.66 to 0.74, timber volume from 0 to 2,500 ft^3/acre, and timber basal area from 0 to 125 ft^2/acre. It is difficult to accurately control the estimates of eight coefficients in linear and nonlinear form over the full range of combinations with a small amount of data. Therefore the parameters are not necessarily functionally related to the physical processes which control the water balance.

In figure 18 the model provides graphical estimates of streamflow for three winter precipitation levels and a range of basal area levels. To illustrate use of the curves, we would estimate that streamflow will be increased 0.6 inch if basal area is reduced uniformly from 120 to 60 ft^2/acre in a situation where winter precipitation is 15 inches. The model predicts 4.3 inches of streamflow as an average for watersheds on Beaver Creek with 16 inches of winter precipitation and basal area of 116 ft^2/acre. Actual streamflow from these same watersheds is 5.3 inches. For estimating response to strip or patch cutting, it is probably best to consider the clearcut openings to be zero basal area, and use actual basal area for remaining timber stands.

Since on the average, only 5 years of posttreatment data are available from Beaver Creek, predicted responses should only be used to estimate average response for a limited period following treatment. This average response will decrease with time after treatment, and is estimated to be of no practical importance after 20 years.

Over a 14-year period on three watersheds, the model is predicting about 20 percent below derived streamflow (table 8). When all observations from the 12 pine watersheds are considered 69 percent of the variation in streamflow is accounted for by the regression, with the majority being accounted for by winter precipitation. The regression model generally underestimates yields, but is relatively consistent even in an unusually high runoff year such as 1973.

The model was also tested on data from the East and West Fork ponderosa pine watersheds on Castle Creek in east-central Arizona (table 9). East Fork, which is used as the control, has a timber basal area of 122 ft^2/acre. Its insolation is estimated to be 0.61. West Fork, where timber was commercially harvested by prescription, had pre- and posttreatment timber basal areas of 135 and 63 ft^2/acre, respectively. The insolation on West Fork is estimated to be 0.72 (Rich 1972).

The 16-year average actual streamflow on East Fork is 2.8 inches, compared with a predicted average of 2.7 inches (table 9).

The pretreatment 11-year average actual streamflow on West Fork is 2.2 inches and the predicted mean is 2.9 inches; the posttreatment 5-year average of actual streamflow is 2.0 inches and the predicted mean is 1.9 inches.

The regression model predicted average pretreatment streamflow for West Fork of Castle Creek within 32 percent and posttreatment streamflow within 6 percent. The long-term mean — including pre- and posttreatment periods — was estimated within 21 percent of the actual. The model estimated a streamflow response of about 0.3 inch, whereas the "actual" response determined by averaging individual

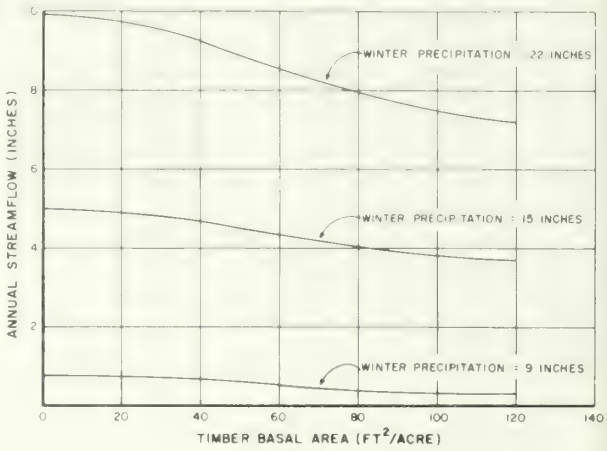

Figure 18.—Predictions of annual streamflow by regression analysis based on winter precipitation, insolation, and timber basal area.

Table 8.--Comparison of observed and predicted streamflow (inches) from three watersheds on Beaver Creek

Water year	Watershed 8		Watershed 13		Watershed 18	
	Observed	Predicted	Observed	Predicted	Observed	Predicted
	Inches					
1960	--	--	3.89	4.90	--	--
1961	2.44	3.26	.94	2.37	--	--
1962	9.23	5.41	4.68	4.50	--	--
1963	.52	1.92	.37	.63	0.30	1.52
1964	2.60	3.92	1.76	1.90	3.09	3.52
1965	13.73	9.09	7.78	6.57	12.34	9.01
1966	10.60	6.58	6.26	4.93	11.95	7.57
1967	3.23	3.71	1.89	1.47	7.46	6.19
1968	8.67	5.73	3.90	4.08	6.03	5.42
1969	11.41	8.07	5.72	4.70	8.45	7.25
1970	3.63	3.42	2.78	1.66	4.88	3.87
1971	1.39	1.44	.37	0	1.03	.80
1972	3.30	2.07	2.15	.36	2.50	.94
1973	16.50	13.78	13.22	11.95	18.51	12.84
Mean	6.71	5.26	4.12	3.57	6.96	5.36
Standard deviation	5.22	3.47	3.52	3.15	5.56	3.73
	Percent difference between means					
	-22		-13		-23	

Table 9.--Comparison of observed and predicted streamflow (inches) from East Fork and West Fork watersheds on Castle Creek in eastern Arizona

Water year	Winter precipitation[1]	West Fork		East Fork	
		Observed	Predicted	Observed	Predicted
PRETREATMENT		- - - *Inches* - - -			
1956	7.66	0.03	0.00	0.06	0.00
1957	11.18	1.50	1.52	1.73	1.75
1958	19.46	5.87	5.81	7.72	6.28
1959	10.36	.65	1.05	1.56	1.27
1960	17.42	3.40	4.82	4.98	5.24
1961	12.26	.14	2.12	.22	2.39
1962	19.70	4.31	5.92	6.58	6.40
1963	13.43	1.26	2.76	1.86	3.06
1964	9.96	.99	.82	1.44	1.02
1965	13.11	1.60	2.59	2.59	2.88
1966	15.85	4.08	4.03	5.90	4.40
Mean	13.67	2.17	2.86	3.15	3.15
Standard deviation	3.98	1.93	2.03	2.67	2.16
		Percent difference between means			
		+32		0	
POSTTREATMENT		- - - *Inches* - - -			
1967	6.66	.86	.00	.87	.00
1968	18.20	7.73	6.20	8.78	5.64
1969	10.15	.77	1.24	.28	1.14
1970	11.16	.44	1.88	.23	1.74
1971	6.18	.03	.00	.00	.00
Mean	10.47	1.97	1.86	2.03	1.70
Standard deviation	4.83	3.24	2.56	3.78	2.32
		Percent difference between means			
		-6		-16	
LONG-TERM AVERAGE		- - - *Inches* - - -			
		2.10	2.55	2.80	2.70
		Percent difference between means			
		+21		-4	

[1]October 1-April 30

yearly responses was 0.5 inch. The regression estimate for the combined pre- and posttreatment periods on the EastFork of Castle Creek was within 4 percent of the actual.

This limited test indicates that average streamflow can generally be estimated within 20 or 30 percent of the actual in the ponderosa pine type with volcanic soils and climate similar to those on Beaver Creek. Error in streamflow estimates for individual years may be larger, and the model cannot be used on the more permeable sedimentary and alluvial soils without some adjustment.

Rogers' System Theoretic Hydrologic Model

Rogers (1973) has developed a model of the hydrologic behavior of a managed natural ecosystem, following concepts published by Wymore (1967, 1972). The model assumes that an ecosystem may be divided into relatively homogeneous land units and channel reaches. It requires as inputs inventory data describing physiographic and vegetative conditions on each unit and reach, along with information on climate and treatments. It operates on a time interval varying from 5 minutes to 12 hours.

The water and energy balance are computed on each unit of the ecosystem. Water yields are routed from unit to unit and into the channel system. Major processes modeled include those affecting canopy interception, snowpack water and energy balance, mulch layer water balance, surface water balance and overland flow routing, evapotranspiration, soil water balance, interflow routing, and channel routing.

Rogers (1973) includes a computer program for implementing the model, together with instructions for its use. He also gives a procedure for developing the required input data.

The model was independently tested on paired Watersheds 12 and 13. Twelve years of data were available. Watershed 12 had been clearcut after the seventh year while Watershed 13 was a control. The predicted mean (5.27 inches) and standard deviation (4.85) of annual flows for the clearcut watershed was approximately the same as the observed (5.42 and 4.27, respectively, table 10). The predicted mean (1.96) and standard deviation (1.91) for the untreated watershed were significantly less than the observed, however (3.10 and 3.08, respectively).

Comparisons of actual and predicted hydrographs (fig. 19) indicate that, in general, the predicted daily flows follow the same general pattern as the observed flows. During the 1960, 1961, 1963, 1964, 1965, and 1966 calendar years the model generally predicted the start of snowmelt period and time of peak flows to within several days. However, the volumes of peak flows were generally outside the error limits. In 1959 the December melt period was not predicted, and in 1962 the early melt period was missed although later ones were predicted. In 1969 the time of major peaks was predicted although the smaller ones were missed, and in 1971 most of the later peaks were predicted although the first one was missed. For the 150- to

Table 10.--Comparison of observed and predicted streamflow (inches) from two watersheds on Beaver Creek (Rogers' system theoretic hydrologic model)

Calendar year	Watershed 12		Watershed 13	
	Actual	Predicted	Actual	Predicted
	- - - Inches - - -			
1959	1.40	0.39	0.73	0.20
1960	4.18	9.91	3.16	3.90
1961	1.83	1.09	.95	.54
1962	7.56	5.36	4.68	2.15
1963	.75	.37	.37	.18
1964	3.15	2.53	1.75	1.17
1965	14.64	16.41	11.62	6.80
1966	5.83	6.26	3.19	1.90
1967	2.95	.51	1.10	.26
1968	10.22	7.17	3.90	1.97
1969	10.63	8.71	5.72	2.60
1970	5.78	8.46	2.78	3.40
1971	1.51	1.38	.37	.44
Mean	5.42	5.27	3.10	1.96
Standard deviation	4.27	4.85	3.08	1.91
Percent difference between means		-3		-36

200-year Labor Day Storm of 1970,[8] the model overestimated the actual flows.

It is difficult to evaluate the model's performance with these limited test results.

Primary sources of error appeared to be in the climatic inputs, some of which had to be estimated, and in modeling the various effects of treatments on soil and vegetation conditions. More comprehensive testing is needed.

Timber Yield Simulation Model

The first attempt at timber yield modeling on Beaver Creek was a regression model developed from the pine watershed data. The eight independent variables tested included annual precipitation, insolation, soil depth, cubic-foot volume, winter precipitation, elevation, percent cinders, and trees per acre. An equation using the first four independent variables for estimating cubic-foot volume growth accounted for 72 percent of the variation. This predictive ability may be improved by stratifying the watersheds by density and site classes instead of using a

[8]*Baker, Malchus B., Jr., Harry E. Brown, and Norman E. Champagne, Jr. Hydrologic performance of the Beaver Creek watersheds during a 100-year storm. Paper presented at Amer. Geophys. Union meeting, San Francisco, Calif., 19 p. Dec. 1971.*

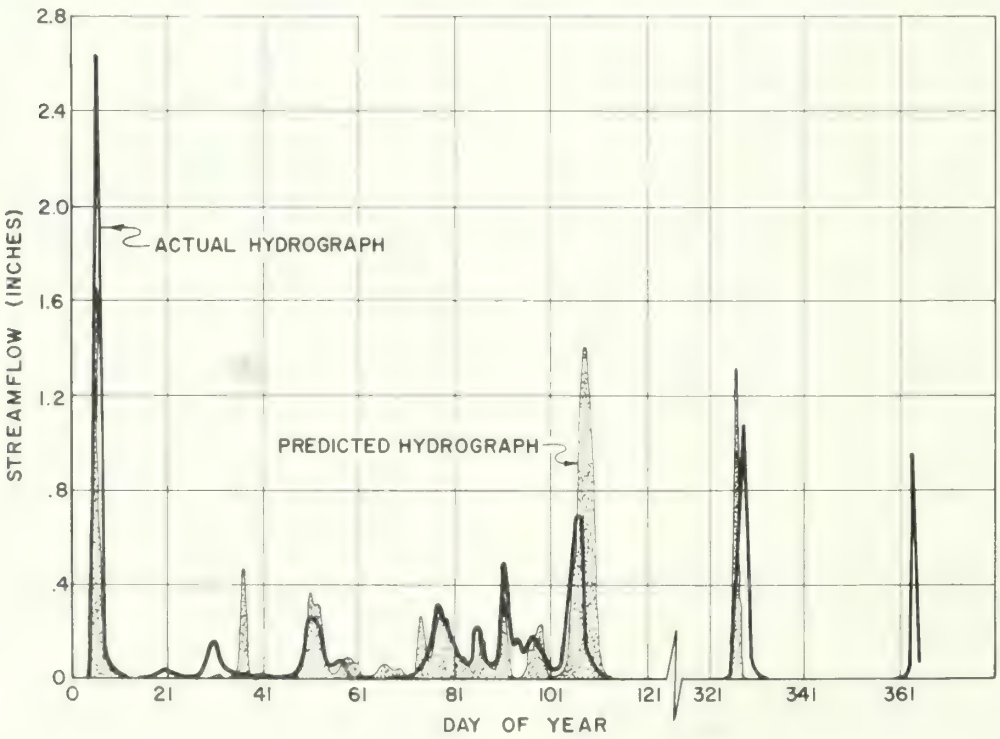

Figure 19.—Test of the Rogers' system theoretic hydrologic model (Watershed 12, 1965).

watershed average. Regression models will never simulate actual stand development, however, because they are unable to accurately duplicate all of the functions representing regeneration, growth, and mortality.

Due to the limitations of regression models, a simulation model is now being developed which employs functions for seed dispersal, germination, seedling survival, tree growth, competition, and mortality.[9] This model is primarily for unevenaged stands, but can be used to estimate future stocking of evenaged stands as well. The model simulates growth of trees through twenty-two 2-inch diameter classes including a zero diameter class for trees less than 1 inch in diameter, and an establishment class for regeneration.

The model is initialized for each stand by reading site index, stand density level (basal area) of residual stand following harvests, time (years) of harvests, type of harvests, and the initial stocking table.

Numerous functions control regeneration in the model. Cone production is a function of stand density and number of trees per acre in cone-producing size classes. Seed production is a function of the number of cones and the number of seeds per cone. Seedling germination and survival depend on total crown cover, seed viability, and expected losses due to rodents, birds, and other factors.

Growth rate is controlled by site index, stand density, and tree size class. A modified stand table projection is used to move a proportion of the trees into the next higher diameter class or classes. The current model uses a 10-year time step for each growth period.

A parabolic mortality function is employed to reflect the higher mortality rate in small and large diameter classes and the relatively low rate in the intermediate classes.

A height-diameter curve is generated for each simulation run. This curve is a function of site index and average growth rate. The generated curve is used in volume calculations which reflect the differences of tree form due to site quality.

Simulation runs have been made to determine projected timber yields for the two dominant soil types on Beaver Creek, over a range of stand density levels (fig. 20). The board-foot volumes projected by the model are consistent with results from other studies (Schubert 1974; Clary et al.[10]) in that yield potential is maximum

[9]*Larson, Frederic R. Simulating growth and management of all-aged southwestern ponderosa pine stands. (Ph.D. Diss. to be completed in 1975.)*

[10]*Clary, Warren P., William H. Kruse, and Frederic R. Larson. Cattle grazing and wood production under different ponderosa pine stand densities. Unpubl. ms. Rocky Mt. For. and Range Exp. Stn., Flagstaff, Ariz.*

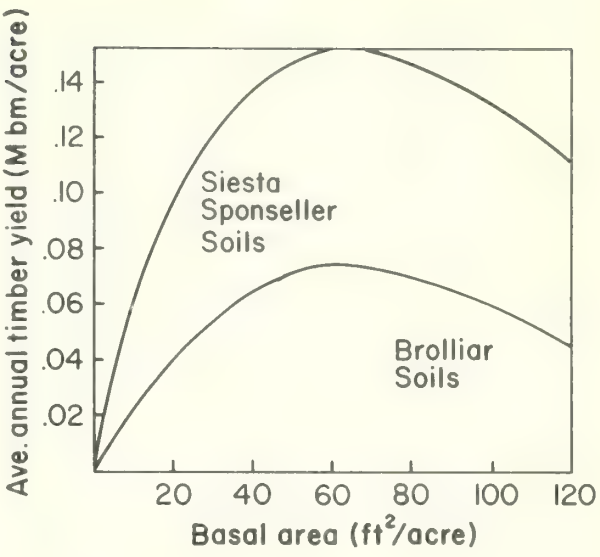

Figure 20.—Sawtimber yield as a function of basal area, for two soil types on Beaver Creek. Larson's model (see text footnote 9) was used to simulate total yield of intensively managed stands over a 140-year period; this amount was then averaged to obtain the estimates of annual yield.

at or near the 60-ft²/acre density level. The projections by Schubert (1974) indicate higher production is possible on better sites, but the general shape of the curve is similar to those generated by this model.

The projections by Schubert (1974) and Clary et al.[10] indicate that annual **cubic-foot** volume growth increases with stand density until the 60-ft² level is reached, and then levels out through the balance of the density levels tested. Larson's cubic-foot volume projections differ from these in that production falls off as basal area increases over 80 ft²/acre. The differences in these projections may be due to initial structure. Schubert's projections are based on evenaged stands carried through maturity. Clary's projections are based on average annual growth rate of pole-sized stands. Beaver Creek stands, on the other hand, are typified by an abundance of saplings and small poles, a shortage of small sawtimber, and an abundance of overmature sawtimber.

A timber yield model developed by Myers (1973) has also been tested. This model, developed for evenaged stands in the Black Hills, uses a regression equation to estimate future diameters of evenaged stands. Since regeneration is not a problem in the Black Hills, the model does not contain functions for cone production, seed production, germination, and survival. Growth rate is simply a function of site,

present diameter, and stand density. Not accounting for regeneration problems, both cubic-foot and board-foot volume projections from Myers' model were about 65 percent greater than those for the same site and initial values projected by Larson's model.

Evaluating Management Alternatives

The previously described models can now be used to provide limited assistance in land use planning. With their help the consequences of alternative management practices can be arrayed in a way that will allow the manager to judge which practices best meet his objectives. Such arrays will eventually be prepared using mathematical programming methods, but meanwhile the procedure can be illustrated graphically with production functions. These functions show how the output of a particular product, such as water, timber, or herbage, responds to increasing degrees of treatments, which in turn are a function of increasing amounts of variable inputs, such as labor, equipment, and materials. General concepts of production functions as they apply to multiple use management were discussed by Lloyd (1969), and some preliminary examples were presented by O'Connell and Brown (1972).

The functions use different levels of timber basal area as the treatment input. Thus to estimate response to a uniform thinning treatment, average pre- and posttreatment basal areas are used to characterize the treatment. For strip or patch cut treatments zero basal area is used for the cleared portion of the management unit, and actual basal area for the remaining portion. This rather gross treatment characterization admittedly imposes certain limitations on the functions — for example they are not sensitive to size, shape, or orientation of forest openings or to juxtaposition of treated areas. Nor do they accommodate treatment features other than forest density reductions, such as planting, seedbed preparation, fencing, salting, and so forth. Nevertheless, forest density manipulations are an important part of most management prescriptions, and even crude applications such as these will provide general management guidelines.

Figure 21 shows preliminary single production functions for sawtimber yield, herbage production, esthetic preference, deer use, streamflow, peak stream discharge, and sediment as functions of timber basal area. These functions have been developed for average conditions on Beaver Creek. They are of varying reliability at this point of development. The best functions are probably those for streamflow and herbage, followed by sediment and

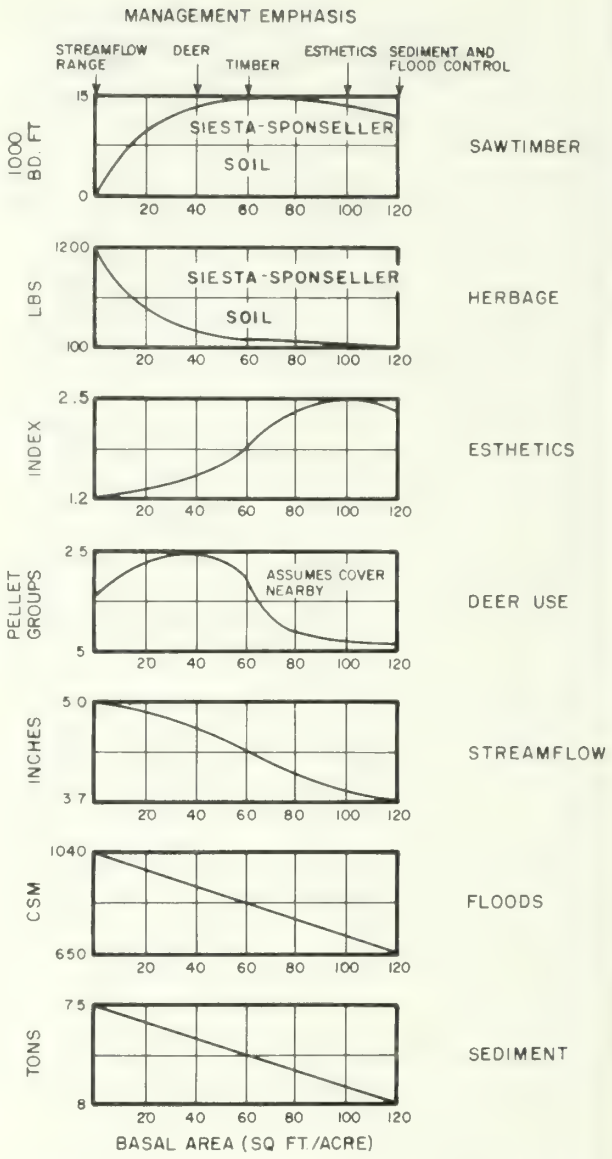

Figure 21.—Example of a multiple use evaluation of alternative management practices (basal area levels) designed to emphasize different uses.

peak discharge, all of which were developed by regression analysis. The other curves were handfitted to more limited data. Applicability of the functions elsewhere has not been tested yet except in the case of the streamflow regression (see previous section).

Table 11 shows the above information as percentage changes. From these data one can determine at what basal area level a particular resource or impact is maximized, or stated another way, the level at which to operate to achieve a particular management emphasis. Of course, in this context some management

Table 11.-- Percent changes in products and impacts resulting from basal area reduction

Effect on --	Management emphasis corresponding to basal area reduction from 120 ft²/acre to:				
	0 (Range and streamflow	40 (Deer use)	60 (Sawtimber)	100 (Esthetics)	120 (Flood and sediment control)
BROLLIAR SOILS:			*Percent*		
Sawtimber *(Mbm/acre/yr)*	-100	44	67	31	0
Herbage *(lbs/acre/yr)*[1]	627	136	82	18	0
Scenic quality index	-152	-168	-183	9	0
Deer use *(pellet groups/acre/mo)*	192	317	150	17	0
Streamflow *(inches/yr)*	35	25	17	4	0
Flood peaks *($ft^3/s/mi^2$)*	62	40	30	9	0
Sediment *(tons/acre/yr)*	838	550	412	138	0
SIESTA-SPONSELLER SOILS:					
Sawtimber *(Mbm/acre/yr)*	-100	23	34	18	0
Herbage *(lbs/acre/yr)*	991	182	118	27	0
Scenic quality index	-152	-168	-183	9	0
Deer use *(pellet groups/acre/mo)*	192	317	150	17	0
Streamflow *(inches/yr)*	35	25	17	4	0
Flood peaks *($ft^3/s/mi^2$)*	62	40	30	9	0
Sediment *(tons/acre/yr)*	838	550	412	138	0

[1]Herbage relationships similar to those in figure 21 are also available for Brolliar soils.

emphases differ by only 20 ft² of basal area, such as flood and sediment control (120 ft² of basal area) and esthetics (100 ft² of basal area). Such differences cannot be assumed to be statistically significant because of the lack of precision. Within these limitations, however, such functions might still be used to conceptually suggest optimum basal area levels for particular management emphases.

The production functions also provide a basis for estimating differences in products resulting from various levels of basal area. For example, if the basal area is reduced from 120 to 60 ft²/acre on Brolliar soils, streamflow will be increased 0.6 inch, or 17 percent. Sawtimber production resulting from this amount of basal area reduction would increase an estimated 29 fbm/acre/year, or 67 percent. Herbage production would be increased an estimated 90 pounds per acre, or 82 percent.

Physical product-product relationships provide another tool for evaluating management responses. They show graphically how two products or environmental impacts respond to land treatments. If price information is available it is possible to derive economic product-product functions that can be used to determine the most efficient combination of products.

The physical product-product curves are formed by connecting points representing paired outputs at a series of basal area levels. The curves in figures 22 and 23 were prepared from paired outputs from figure 21.

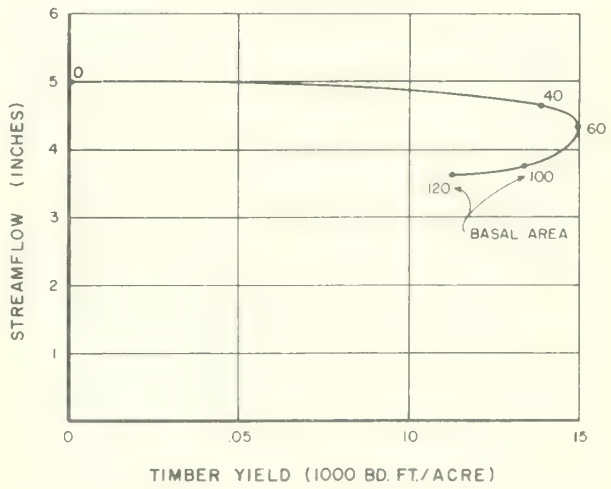

Figure 22.—Product-product function for streamflow-timber. The curve shows relative yields of both products at different basal area levels. As forest density is reduced from 120 to 60 ft², both streamflow and timber yields increase. Below 60, streamflow continues to increase but timber yields decline. One possible interpretation is that basal area should be reduced to 60 because both streamflow and timber yields are increasing to that point.

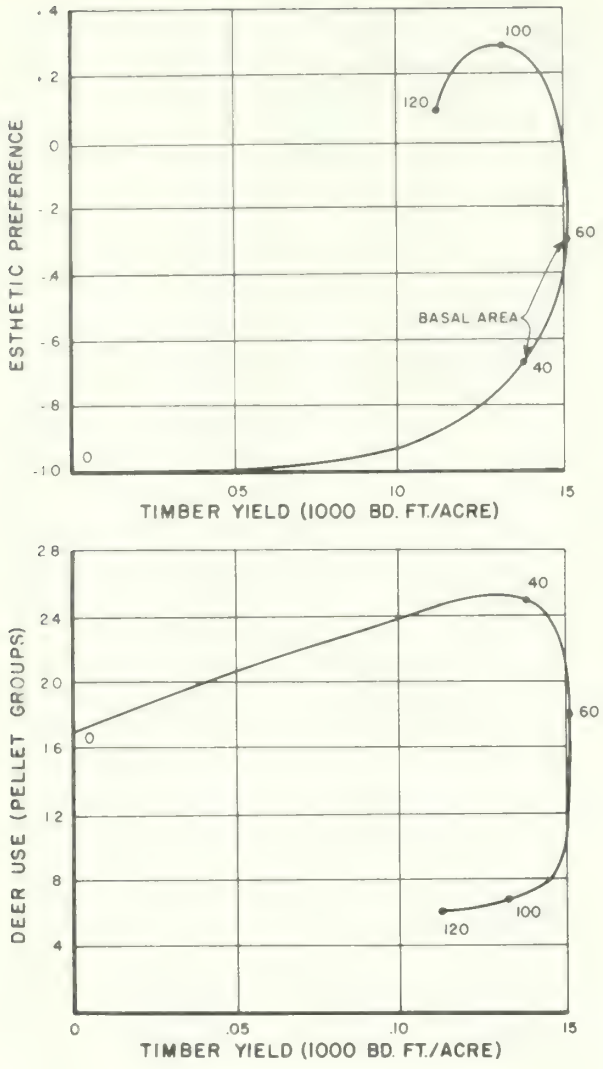

Figure 23.—Product-product functions for esthetics-timber and deer use-timber. Esthetics and timber production both increase as basal area is reduced from 120 to 60. The curve suggests a compatible operating level between 60 and 100. Deer use and timber both increase at basal areas down to 60; this curve suggests a suitable operating level between 70 and 40.

The physical product-product curves can be interpreted by observing the change in the two products as basal area is reduced from a starting level of 120 ft²/acre. If both products are increasing as basal area is reduced, other things being equal, the manager would be inclined to continue lowering the basal area. This is the complementary phase of the curve. When the point is reached where only one product is increasing and the other is constant or decreasing, there is less incentive to continue reducing basal area. It is in this range that the manager would be likely to establish the treatment level. There is little justification for operating in the third phase where both products are decreasing (illustrated in fig. 22). The captions in figures 22 and 23 state some of these interpretations, the assumptions being that only two products are being considered at a time and that costs are not limiting.

Physical product-product curves for numerous other combinations of products or impacts can be prepared and interpreted similarly; however, not all products or impacts have the same influence on decisionmaking.

Turner (1974) has shown in more detail how the relationship can be used in the development of management prescriptions, considering costs and values of all products and impacts together.

If carried to the extreme there could be different production functions for all important combinations of soil, vegetation, climate, and physiography. Hopefully, however, improved models of ecosystem behavior can be developed that will produce the same information in a more efficient manner.

Meanwhile, the regression models tested so far have quantified a limited number of site factors affecting resource production and environmental impacts. These are summarized as follows:

Products and impacts	Influencing factors				
	Timber density	Soil	Winter precipitation	30-min. precipitation intensity	Insolation
Timber	X	X			
Herbage	X	X			
Esthetics	X				
Deer use	X				
Streamflow	X		X		X
Flood peaks	X			X	
Sediment	X			X	

Needed Research to Provide Better Management Tools

Improved analytical procedures and data are needed for predicting quantity and quality of trade offs among major products, services, and environmental values of ponderosa pine lands in the Southwest. Past research has provided considerable information on the effects of selected management practices under specific conditions on yields of individual market products such as water, timber, and forage. But little information is available on the various

combinations of these products that are attainable from specific management units. Less is available on trade offs between market products and the many nonmarket products and environmental values attainable from a given area.

In this paper some analytical procedures have been presented along with accompanying arrays of multiple use response data. Before these procedures and data can be widely used, however, the capabilities of the various predictive models must be substantially enhanced and their performance tested over a wide range of conditions. Some particularly important needs are:

- Improved performance of hydrologic models to allow better estimates of usable water yield from porous sedimentary and alluvial soil types.
- Improved capabilities for estimating hydrologic responses of various forest cutting patterns and size class distributions.
- Timber yield simulation models that are sensitive to soils, site index, soil water and nutrients, and solar energy. Timber yield models should be capable of responding to a variety of harvesting schemes as well as to disasters such as insect, disease, and mistletoe outbreaks and fire. The models will need to include tested functions for regeneration, growth, and mortality.
- Functions to describe the quantity of fuels for fire hazard prediction.
- Improved capabilities for modeling the response of wildlife habitat and populations to alternative management practices.
- Improved capabilities for estimating nutrients and other factors that affect site productivity.
- Improved capabilities for predicting esthetically pleasing landscapes that will be compatible with land treatment practices designed for other objectives.

A computerized data bank should be developed to accommodate resource characteristics data, climatic data, process or validation data, and predictive output data from alternative modeling systems. Such a data bank should include all available data from the several experimental watersheds in the southwestern ponderosa pine type (Beaver Creek, Castle Creek, Thomas and Willow Creeks, Black River Barometer, and Workman Creek). Also included should be data from the small homogeneous subwatersheds currently being instrumented on Beaver Creek and elsewhere for model testing and validation.

Operational versions of the above models should be developed in conjunction with National Forest Systems, along with an operational data bank and inventory system.

The entire multiple use management planning system should be pilot tested, including inventory, data bank, response models, and economic and management models. Such pilot tests will be necessary to improve the various models and procedures, and to show users as well as the general public how these management planning procedures actually work.

Sensitivity analyses should be performed on the response and management models to determine which variables are most important in the decisionmaking process, and what gaps require additional research. On the basis of these sensitivity tests, research efforts will be reorganized to allow the most efficient and expeditious development of the models into a form widely useful throughout the region.

Conclusions

In summary, four principal resource responses are known to result from manipulating ponderosa pine forests growing on volcanic soils:

- Water yield increases of 1 to 2 inches per year over a 5-year period have been realized as a result of various intensities and patterns of timber reduction. On the more productive pine areas, an average increase of 0.6 inch per year may be realistic, in light of present multiple use consideration and environmental constraints.
- Preliminary results of a timber simulation model suggest that harvestable timber volume growth may be increased even after a considerable reduction of timber basal area.
- Timber overstory reduction results in an increase in understory plant production. Herbage production can increase 500 pounds per acre per year on low to moderately productive soils as the result of complete overstory removal.
- In general, deer and elk habitat are improved by opening up the ponderosa pine canopy to enhance understory forage supply.

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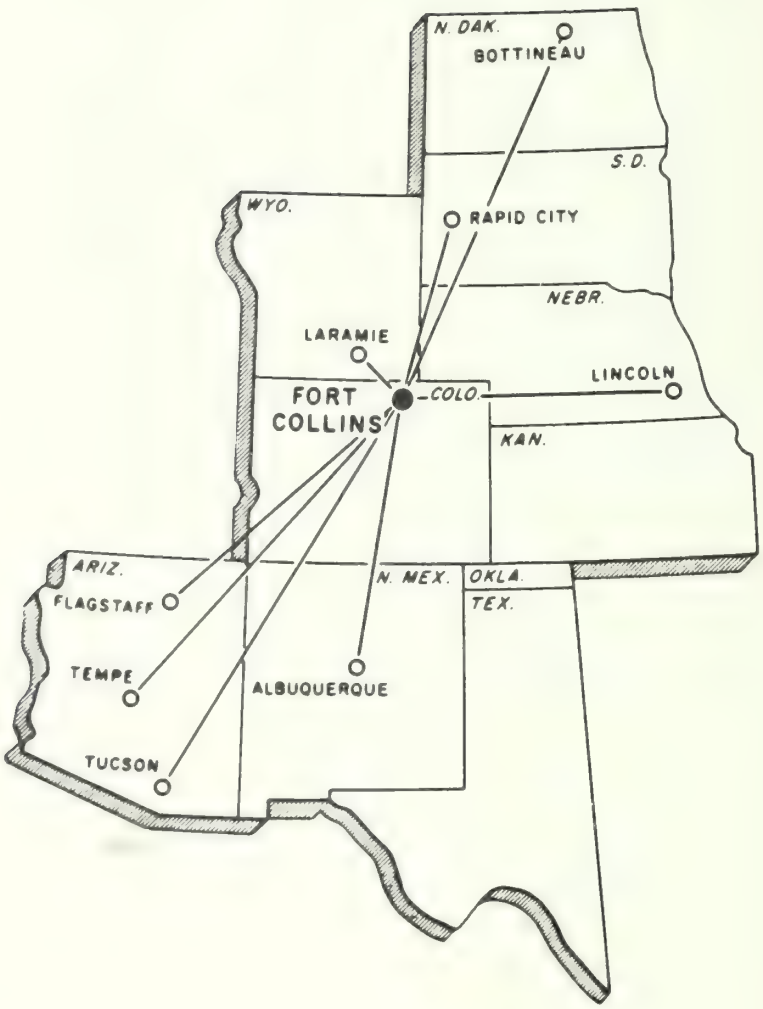
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Rocky Mountain Forest and
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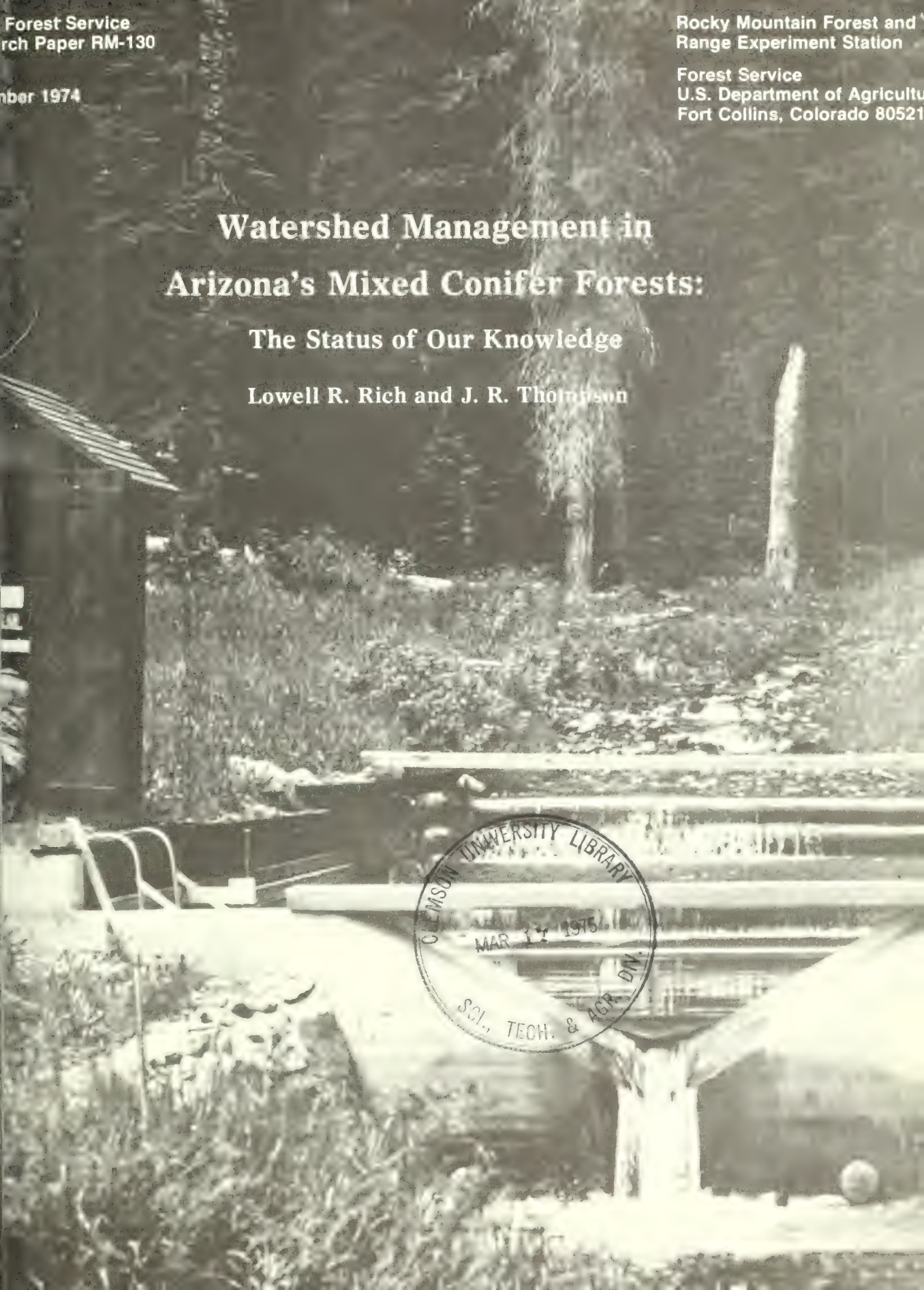
Watershed Management in Arizona's Mixed Conifer Forests:

The Status of Our Knowledge

Lowell R. Rich and J. R. Thompson



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Abstract

Removing mixed conifer forest vegetation has increased water yields approximately in proportion to the percent of the area in cleared openings. Most of the yield increase can be accounted for by the reduction in evapotranspiration. Reduced soil-moisture deficit and increased snow accumulation and melt rates in the cut openings contribute to these increases. When fitted to the timber-stand structure, patchcutting is (1) compatible with recommended mixed conifer silviculture, (2) beneficial to wildlife, and (3) esthetically pleasing. Although mixed conifer areas make up only 0.4 percent of the total land area of Arizona, they contribute 6 percent of the State's water yield. Intensive management of these forest lands could increase annual streamflow 36,500 acre-feet per year—roughly 12 billion gallons of water per year.

Keywords: Water yield improvement, mixed conifer, sediment yield.

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USDA Forest Service
Research Paper RM-130

December 1974

Watershed Management in Arizona's Mixed Conifer Forests: The Status of Our Knowledge

by

Lowell R. Rich, Principal Hydraulic Engineer
and
J. R. Thompson, Principal Meteorologist
Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters maintained at Fort Collins, in cooperation with Colorado State University; authors are located at Tempe, in cooperation with Arizona State University. Rich is now retired.*

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Watershed Management in Arizona's Mixed Conifer Forests: The Status of Our Knowledge

Lowell R. Rich and J. R. Thompson

Introduction

All available evidence still supports the hypothesis that, ". . . modification of the various vegetation types, is . . . promising for increasing the water supply . . ." (Barr 1956). Throughout the Rocky Mountains, the mixed conifer type has often been emphasized in water-yield improvement research because the potential for increase appeared greatest there.

Watershed management research in Arizona dates from the formal establishment of the Sierra Ancha experimental watersheds on the Tonto National Forest in 1932. Although water yield has often received primary emphasis, forage, timber, and other resources have always been considered as important and integral parts of the total watershed ecosystem. This Paper summarizes the results of water yield studies that apply to Arizona's mixed conifer vegetation association, and hopefully provides a foundation from which alternative forest management practices can be more easily evaluated.

Description of the Area

The high water-yielding areas of the Southwest are those with major water surpluses as a result of precipitation exceeding evapotranspiration (Fletcher and Rich 1955). This delineation coincides closely with the mixed conifer and aspen forests. Sometimes referred to as the pine-fir, spruce-fir, and Douglas-fir types, the mixed conifer includes those timber stands above approximately 7,000 ft, where ponderosa pine makes up about 60 percent or less of the total volume. It is a highly diversified type (fig. 1), including a wide mixture of: Engelmann spruce (*Picea engelmannii* Parry); blue spruce (*Picea pungens* Engelm.); Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco); white fir (*Abies concolor* (Gord. & Glend.) Lindl.); corkbark fir (*Abies lasiocarpa* var. *arizonica* (Merriam) Lemm.); ponderosa pine (*Pinus ponderosa* Laws.); southwestern white pine (*Pinus strobiformis* Engelm.); quaking aspen (*Populus tremuloides* Michx.); Arizona alder (*Alnus oblongifolia* Torr.), bigtooth maple (*Acer grandidentatum* Nutt.); Arizona walnut (*Juglans major* (Torr.) Heller); New-Mexican locust (*Robinia neomexicana* A. Gray); and Gambel oak (*Quercus gambelii* Nutt.).

There are approximately 240,000 acres of mixed conifer in Arizona (Spencer 1966). Although aspen is often an associate species, it also occurs in pure stands as a climax (or fire climax) species. For this paper, we consider Arizona's 79,000 acres (Spencer 1966) of aspen as a part of the mixed conifer type, making a total of 319,000 acres. Although the mixed conifer and aspen cover only 0.4 percent of the State's area, they produce more than 6 percent of the State's surface water, greater than 10 times their proportionate share.

Only a small part of the total precipitation that falls on Southwestern watersheds is recovered as streamflow. Of an estimated 83 million acre-ft of annual precipitation in Arizona, 76.7 million are lost to evapotranspiration alone (Kelso et al. 1973). Channel losses, ground water, and other factors account for an additional 3.4 million acre-ft. Research has shown that vegetation manipulations can increase water yields by decreasing evapotranspiration.

The ever increasing demands on wildlands by an expanding population is particularly noticeable in the mixed conifer, with its associated meadows and aspen stands. Not only is the timber of high value, and water a prime concern because of its quality and quantity, but also the esthetics and wildlife are important to the recreationist or transient tourist. The cool summer climate makes the area highly attractive for summer homes.

Figure 1.—The mixed conifer type is a highly diversified mix of eight principal tree species, interspersed with grassy meadows.

The mixed conifer is a prime habitat for such species as elk, deer, bear, turkey, grouse, squirrel, and numerous songbirds. Trout fishing is almost totally dependent on the cool, clear waters that come from the lands of this vegetation type. Forage production in the parks and open meadows is higher than in most other areas of the Southwest, making them valuable summer range for livestock.

In general, the mixed conifer stands in Arizona occur where the annual precipitation averages more than 30 inches. Summer (May-

September) and winter (October-April) precipitation are almost equal, but 75 percent or more (often as high as 90 percent) of the streamflow comes from winter snowfall. Soils are predominantly basalt-derived Sponseller, with medium to moderately fine texture, and porous. Soil depth varies over a wide range, but in general could be classified as moderately deep.[2]

Research Background

Many factors—such as precipitation, interception, evaporation, transpiration, cloud seeding, cover characteristics, and channel conditions—influence water yields. Vegetation exerts a strong influence on many of these factors, and because vegetation is amenable to management by man, man's actions can have a pronounced influence on water yield.

Early Concepts

Many early observers could see the tenacious bond between forests and water. Zon (1912) stated that "Accurate observations . . . establish with certainty the following facts in regard to the influence of forests upon climate; . . . Forests increase both the abundance and frequency of local precipitation over the areas they occupy . . . ." It was theorized that forests caused greater precipitation and therefore spawned the springs and rivers that always had their origin in forest and associated wildlands. Concern was registered by some over the extensive clearing of trees in the Midwest during the 19th century. The fear was not that the forests were being depleted, but that large-scale removal of the forests could diminish precipitation in the area.

Eighteen years ago, Barr (1956) recommended that 3,025,000 acres within the Salt-Verde basin in Arizona be treated for the production of water. Proposed treatments on selected areas included: drastic thinning in pine; removal of Douglas-fir, white fir, and 50 percent of the pine along mountain streambanks; replacement of lowland riparian woody species (phreatophytes) with herbaceous cover; and conversion of pinyon-juniper stands to grass. These, along with other treatments in the proposed action program, were predicted to be capable of increasing streamflow by 285,000 acre-ft per year.

[2]*Leven, Andrew A., and Peter J. Stender. Hydrologic survey and analysis, Black River barometer watershed, Apache National Forest. (Office Rep.) 1967.*

Research results have not supported these optimistic predictions. Pinyon-juniper conversions on Beaver Creek have not affected water yield (Brown 1970). Thinning treatments in pine on Beaver Creek and mixed conifer on Workman Creek, and removal of riparian vegetation on the North Fork of Workman Creek, likewise have not measurably increased streamflow (Brown 1970, Rich et al. 1961). Although clearing woody phreatophytes has increased streamflow (Horton and Campbell 1974), the portion of this increase lost to replacement herbaceous vegetation is still unknown.

Paired Watershed Experiments

The Swiss, in 1900, were the first to gage a pair of small watersheds to determine the influence of forests on streamflow—one watershed was 98 percent in forest, the other only 30 percent. They concluded that the forest acted to equalize flow through dry and wet periods of the year without diminishing the total yield (Zon 1912). Critics pointed out that there were differences in the two basins besides vegetation differences; therefore, the conclusions were suspect.

The calibrated watershed approach began at Wagon Wheel Gap, Colorado, in 1910. By relating the flow of two similar catchments over a period of years, and then altering the vegetation on one without disturbing the other, subsequent changes in the flow relationship could be attributed to the "treatment." Bates and Henry published their final report on Wagon Wheel Gap in 1928, the first scientific contradiction to the earlier held views of forests and water yield. The new technique spread like wildfire, and scores of paired watersheds were established. Almost invariably these experiments showed that removal of significant amounts of forest vegetation increased water yields (Goodell 1958; Hornbeck et al. 1970; Hoover 1944; Hoyt and Troxell 1934; Johnson and Kovner 1956; Lewis 1968; Love 1955; Martinelli 1964; McGuinness and Harold 1971; Patric and Reinhart 1971; Rich et al. 1961; Rich 1972; and Rothacher 1965, 1970).

Hibbert (1966) in summarizing results from 39 such studies, concluded that, ". . . forest reduction increases water yield, and reforestation decreases water yield." But he went on to say that wide variations among individual treatment results made predictability uncertain. Because conclusions drawn from paired watershed studies included such qualifying statements as "similar effects may not neces-

sarily hold for different climatic, soil, and vegetative conditions," proponents of the approach were forced to return to basic hydrologic studies to explain and use their results.

Plot Studies

Decreased snow interception losses following forest cutting was once believed to be a major cause of increased streamflow. Hoover and Leaf (1966) found, however, that mechanical removal and transport of intercepted snow was more important than vaporization in lodgepole pine and Engelmann spruce in Colorado. In ponderosa pine in Arizona, Tennyson (1973) concluded that "Most of the intercepted snow reached the snowpack on the gound, representing no significant loss to the water budget on site."

Reduced evapotranspiration seems to be the principal reason for increased water yield when forest openings are created. Kovner (1956) showed that the increase in streamflow after removing all forest vegetation on an oak-hickory watershed, "... was due to a corresponding decrease in the amount of evapotranspiration." Data from the Fraser Experimental Forest indicate that decreased evapotranspiration losses in cut strips in lodgepole pine and Engelmann spruce, along with redistribution of the snowpack, are the main factors explaining increased water yield (Hoover and Leaf 1966).

In Southwest mixed conifer forests, regrowth of trees in clearings cut for water yield improvement may not adversely affect the yield increase for some time. This conclusion is based on several factors, the combination of which is unique to this area: (1) snowmelt is the primary source of streamflow, (2) summer rains are normally adequate to satisfy evapotranspiration requirements during the growing season, (3) the supply of solar energy is high, and any changes in the surface albedo are therefore more pronounced in affecting the net energy level, and (4) soils are porous, allowing rapid infiltration and drainage.

Shading is, undoubtedly, the key element affecting water yield increases from forest patchcutting. It is responsible for reducing evapotranspiration in the opening by decreasing radiant energy. Shading also can effectively reduce the size of root systems (Kramer 1969). Depth and extent of the roots obviously affect water use.

Water use studies that compare tree species with brush or grass, consistently show less evapotranspiration for the replacement vegetation. Table 1 summarizes some of these studies that apply to the mixed conifer type.

Research in Arizona

The following paragraphs summarize and interpret the basic treatments and most significant results obtained from the three Workman Creek watersheds, which were instrumented in 1938, and the Castle Creek and Willow-Thomas Creek watersheds, which were installed in 1956 and 1963, respectively. Physical and vegetation characteristics of these watersheds are described in the appendix, along with more detailed descriptions of the treatments applied and results obtained.

The experimental paired watersheds were established to serve as models to produce data applicable to larger areas. Threshold or extreme values were considered the primary need. First treatments applied to the Workman Creek watersheds were to determine the maximum water yields obtainable on one watershed, and to test the effects of practical timber harvest operations on water and sediment yields on another.

Intermediate forest removals were studied at Castle Creek and Willow Creek. Castle Creek watersheds were set up to develop a system of timber management that would improve both water and timber yields and maintain other watershed products. Willow Creek was a second test of the effects of a practical type of timber management on water and sediment yields. The treatment, completed in September 1972, was silviculturally fitted to the existing forest stand of the 490-acre East Fork watershed. Water yield results from Willow Creek will be available in 4 or 5 years.

The Thomas Creek watersheds, another calibrated pair in the mixed conifer, are the last calibrated and untreated watersheds in the White Mountains. For this reason it is planned to gain as much information as possible on multiproduct evaluation of resource management practices from these watersheds. The following are the overall objectives:

1. Validate, refine, and pilot-test resource response models for planning management of mixed conifer stands in the Southwest.

2. Determine and evaluate effects of selected resource management practices on landscape esthetics and other environmental and recreational values.

3. Determine cost, production rates, and environmental consequences of cable logging in mixed conifer forests on steep slopes.

Table 1.--Comparison of average daily evapotranspiration rates for some mixed conifer species, brush, and grass, in different localities

Cover type	Location	Season	Evapotranspiration	Reference
			Inches/day	
Spruce	Alberta	July	0.185	Storr et al. 1970
Spruce	Colorado	July-October	.132	Brown and Thompson 1965
Spruce	Europe	Unknown	.169	Rutter 1968
Fir:	Sweden			
Dry site		May and June	.134	Rutter 1968
Wet site		May and June	.189	Rutter 1968
Douglas-fir	Canada	July	.136	McNaughton and Black 1973
Pine	New Jersey	May-October	.117	Rutter 1968
Pine	Arizona	May-October	.129	Thompson 1974
Pine	Oregon	August	.139	Gay 1971
Aspen	Colorado	June-September	.154	Rutter 1968
Brush	Utah	May-November	.065	Rowe and Reiman 1961
Grassland	Colorado	June-September	.079	Brown and Thompson 1965
Grassland	Utah	May-November	.048	Rowe and Reiman 1961

Water Yield Results

A total of five treatments on Workman Creek[3] and one on Castle Creek, have been evaluated to date. These are: (1) North Fork riparian cut of broad-leaved trees; (2) North Fork moist-site cut of Douglas-fir and white fir with conversion to grass; (3) North Fork dry-site cut of merchantable ponderosa pine with conversion to grass; (4) South Fork individual tree selection cut; (5) South Fork clearcut with planting of ponderosa pine (to eventually achieve 40 ft^2 of basal area per acre); and (6) Castle Creek patchcut—one-sixth cleared, remaining five-sixths put in best possible growing conditions.

The removal of a small quantity of deciduous riparian trees on the North Fork, where a stand of white fir and Douglas-fir remained near the stream channel, did not increase water yields. Similarly, a heavy removal of mature and overmature forest vegetation that left a large residual stand on South Fork did not significantly affect water yields.

Table 2 summarizes the results from the four watershed treatments that significantly increased water yields. These data are plotted in figure 2. Increases in water yields were calculated as the differences between before-treatment and after-treatment regressions. The consistency of the data lends credence to this predictive nomograph, but qualifying statements must be added.

This simple graphic model applies only to mixed conifer types of the Southwest, where conditions are comparable to those of the Workman Creek-Castle Creek areas. The most important of these conditions is probably the percent of annual precipitation occurring as streamflow (annual runoff efficiency). This efficiency is an integrated measure of many watershed factors, such as soil-water recharge requirements, degree to which the vegetation occupies the site, and numerous physiographic factors. Establishing this comparability may

[3]*Rich, Lowell R., and Gerald J. Gottfried. Water yields resulting from treatments on the Workman Creek experimental watersheds. (Manuscript in preparation at the Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.)*

Table 2.--Water yield increases (inches) expected from watershed treatments, computed from regression equations

Watershed and treatment	Yield increase expected from treated watershed if runoff from control watershed is--						
	1 inch	2 inches	3 inches	4 inches	5 inches	6 inches	7 inches
	Inches						
West Fork of Castle Creek							
17 percent of area in clearcut openings, balance of watershed harvested	0.41	0.50	0.60	0.69	0.78	0.88	0.98
North Fork of Workman Creek							
33 percent of area cleared and planted to grass (moist site)	.92	1.15	1.38	1.61	1.84	2.06	2.29
North Fork of Workman Creek							
73 percent of watershed area cleared and planted to grass (dry site)	1.05	2.09	3.13	4.16	5.20	6.24	
South Fork of Workman Creek							
83 percent of area cleared preparatory to planting	1.39	2.66	3.92	5.19	6.46	7.72	

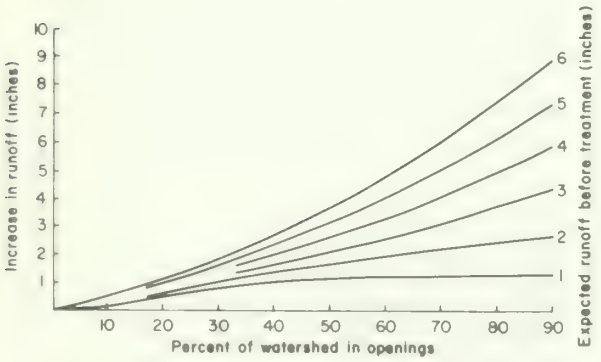

Figure 2.—Potential water yield increases from watershed treatments in pine-fir and mixed conifer vegetation. (Spaces greater than three times the height of the surrounding trees are considered openings.)

not be a serious problem in Arizona's mixed conifer forests, however, because the delineation of the type is itself a measure of many of these conditions. Figure 2 may be used as a predictor in land management planning, subject only to the caution that it is offered as an aid in decisionmaking, not a panacea.

Results presented here are based on clearcutting and patchcutting. Openings in the forest greater than three times the height of the surrounding trees, are effective in redistributing snow and reducing evapotranspiration. In recent years "clearcutting" has become synonymous with vast areas of devastation created in the name of watershed management. Small, irregularly shaped "patchcuts" that promote snow accumulation and reduce soil moisture deficits and evapotranspiration can be esthetically pleasing, improve wildlife habitat by increasing cover diversification, improve herbage production for livestock, and still provide a high quality, sustained yield of timber while increasing streamflow.

Computer simulation of hydrologic results of patchcutting has shown that magnitude of peak flows is not changed significantly, but their timing is altered appreciably. Duration of runoff remains essentially unchanged (Leaf and Brink 1972). Conversely, clearcutting in large, regularly shaped blocks is esthetically displeasing and can drastically alter the seasonal hydrograph. After total clearcutting, the 200-acre mixed conifer watershed at Wagon Wheel Gap produced much greater flood peaks (Bates and Henry 1928). Although the large clearcuts are more easily logged and produce a greater percentage increase in total water yield, the large flood flow is of questionable benefit.

Removal of moist-site forest vegetation—Douglas-fir and white fir—from 80 acres of a 248-acre watershed increased water yields 45 percent. Clearing an additional 100 acres of dry-site forest vegetation—dominantly ponderosa pine—further increased water yields. Compared to original conditions, increases varied from 81 percent at 1-inch yield from the control watershed to 109 percent at 7-inch yield from the control. Clearcutting 83 percent of a 318-acre watershed resulted in water yield increases varying from 91 percent at 1-inch yield from the control watershed to 140 percent at 7 inches from the control. Clearcutting one-sixth of a 900-acre watershed, where the remaining five-sixths of the watershed was placed in the best growing condition possible, increased water yield about 29 percent.

In contrast, annual water yields following the individual tree selection harvest on South Fork of Workman Creek were not significantly changed by the treatment. A substantial amount of timber was removed by this timber harvest and by fire, but the removal was spread over 5 years. Voids in the stand probably filled naturally and quickly, and—also—a comparatively heavy stand of trees remained after the harvest. Even after 46 percent of the basal area of trees on the watershed were removed, 107 ft^2 per acre remained.

A riparian cut of Arizona alder and big-tooth maple adjacent to streams and seeps on North Fork of Workman Creek that removed 0.6 percent of the total basal area of all trees on the 248-acre watershed did not significantly increase water yields.

A second test of forest management on water yields is currently underway, and future multiproduct tests are planned for two additional calibrated watersheds.

Erosion Measurements

Erosion, sediment losses, and the corresponding quality of water depend not only on the type of watershed and the amount and condition of the watershed cover, but also on the point and time of measurement. Sediment losses from a wildfire in South Fork of Workman Creek illustrate these variations (Rich 1962).

The fire was started by lightning on July 6, 1957, and was carried into South Fork of Workman Creek by high winds. Conditions were extremely dry; only 2.97 inches of rain had fallen since March 22. The fire, which crowned in the trees, consumed litter and ground vegetation and killed all but a few large trees along the edge of the 60-acre burn. Immediately after the fire, the area was seeded to grass, and a good stand of grass and New-Mexican locust was established before the end of the summer. Sediment movement following the fire was based on measurements of (1) profiles across random timber sample plots, (2) random cross sections in the lower 3,600 ft of the main stream channel, (3) sediment trapped in the weir ponds, and (4) profile lines across randomly located seeding plots.

The first storm after the fire, on July 16, was one of the heaviest measured in Workman Creek. Total precipitation measured at two gages inside the burn area was 3.50 and 4.05 inches. At the Workman Creek Climatic Station about ¾ mile north of the burn, 3.41 inches of precipitation were recorded between 7 and 11 p.m. Total summer precipitation (June, July, August, and September) was 10.60 inches, only slightly above average.

Profile measurements indicated approximately 1 acre-ft of sediment (an average depth of 0.016 ft) was eroded from the burn. Sediment was deposited immediately below the burn in unburned forest vegetation, in the stream channel, and in the weir pond. Only 818 ft^3 (approximately 2 percent) was deposited in the weir pond. Approximately 39 percent (17,000 ft^3) was deposited in the stream channel between the fire and the weir pond at the lower end of the 318-acre watershed. Most of the remaining sediment was deposited on flat areas just outside the burn.

The amount of sediment trapped in weir ponds from the East Fork of Castle Creek is similar to the prefire value from Workman Creek. Castle Creek vegetation is basically ponderosa pine with mixed conifer vegetation on north-facing slopes. Measuring weirs and ponds were completed during the summer of 1955. Three years later following a year of higher-than-average runoff, 44 yd^3 (1.0 ft^3 per acre per year) were trapped in the East Fork weir pond from a watershed of 1,163 acres. Two years later, 18 yd^3 (0.4 ft^3 per acre per year) were measured in the East Fork pond. In contrast, the adjoining 900-acre West Fork watershed had trapped no sediment in the weir pond during this same pretreatment period (1955-60).

The only sizable amounts of sediment moved from these White Mountain watersheds as a result of a series of thunderstorms in October 1972. During the 2 weeks prior to the major runoff event on October 19 and 20, 7¼ inches of rain had fallen. On October 19, an additional 4 inches fell in a 24-hour continuous storm. Average intensity for this period was about 0.17 inch per hour, with a maximum of 1.15 inches per hour at noon that lasted for a half hour. The peak flows were not much different for the two watersheds (120 $ft^3/s/mi^2$—West

Fork; 125 $ft^3/s/mi^2$—East Fork), but the treated West Fork produced 2.5 times more sediment than the control watershed.

On-the-ground observations during and after this storm event seemed to support the conclusion of Copeland (1969) that logging roads are the primary source of erosion. The treated watershed had considerably more sediment accumulation in the channels, from the years immediately following logging. This flood merely flushed the channels. No erosion was detected on the saturated land surfaces by an observer walking across the watersheds during the height of the thunderstorm. Only slight amounts of soil movement were detected from the old, revegetated logging roads.

Roosevelt Reservoir, about 55 miles east of Phoenix, Arizona, began storing water shortly after the dam was completed March 18, 1911. A survey made in 1925 showed a total accumulation of 101,000 acre-ft of sediment, an average annual rate of accumulation of 7,214 acre-ft or 125.2 acre-ft per 100 mi^2 from the 5,760-mi^2 watershed above Roosevelt Dam (Eakin 1936).

In 1946, total sediment was 142,450 acre-ft. Over the 36-yr period, this indicates 3,957 acre-ft per year or about 68.7 acre-ft per 100 mi^2 of drainage area.

Table 3 compares sediment yields from Arizona mixed conifer watersheds with sediment yields from the Salt River as measured in Roosevelt Reservoir and from Fraser Experi-

Table 3.--Sediment yields from selected watersheds in Arizona and Colorado

Watershed	Size	Vegetation	Period	Average annual sediment production	Remarks
				ft^3/acre	
Salt River above Roosevelt	5,760 miles	Desert to alpine	1911-25	85.2	
			1911-46	46.8	
Workman Creek					
North Fork	248 acres	Mixed conifer	1939-58	0.4	
			1959	2.3	First year after treatment.
			1960	6.2	Second year after treatment
			1970	1.4	Year of maximum storm (11.4 inches in 24 hours)
South Fork	318 acres	Mixed conifer	1939-53	0.14	
	60-acre burn		1957	726	Fire destroyed 74 percent of basal area
	318 acres		1957	14	
	318 acres		1958-60	4.4	
Castle Creek					
East Fork	1,163 acres	Pine-fir	1958	1.0	Fully stocked (control watershed)
			1960	0.4	
			Oct. 1972	0.9	
West Fork	900 acres		1958-60	0	Fully stocked
			Oct. 1972	2.4	1/6 clearcut in 1965-66
Fraser, Colorado					
Fool Creek	714 acres	Lodgepole pine spruce-fir	1952	2.2	Logging roads constructed
			1953	1.1	
			1954-55	0	
			1956	1.8	Timber harvest
			1957-58	2.8	
			1959-65	0.5	
Deadhorse	667 acres		1955-65	0.4	Fully stocked, untreated
Lexen	306 acres		1956-65	0.3	Fully stocked, untreated

mental Forest watersheds in Colorado (Leaf 1966). These data indicate that: (1) the mixed conifer type produces very little sediment compared to the integrated total of all vegetative types in the Salt River basin, (2) road construction and timber harvest increase sediment production, and (3) wildfire is a greater sediment-producing agent than man's logging activities.

Discussion and Conclusions

How forest vegetation affects water and sediment yield has been studied by removing forest vegetation. Some extreme treatments have been applied in manipulating the watershed vegetation to determine threshold or extreme values for research purposes.

Water Quantity

Management can change the yields of water products on experimental watersheds. Clearcutting forest vegetation has increased water yields approximately in proportion to the percent of the area clearcut (fig. 3).

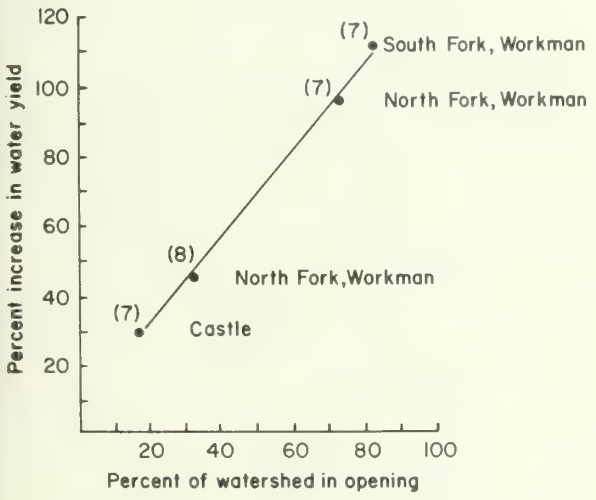

Figure 3.—Water yield increase as a function of the percent of the area in openings.

Most of the yield increase can be accounted for by the reduction in evapotranspiration. Reduced soil-moisture deficit and increased snow accumulation and melt rates in the cut openings are additive factors that contribute to these increases. Water use data from Black Mesa in western Colorado (Brown and Thompson 1965) and evapotranspiration estimates from energy budget data in eastern Arizona (Thompson 1974) both support a 4- to 5-inch reduction in evapotranspiration in the clearcut openings on Castle Creek. Since these openings occupy 153 acres on the 900-acre watershed, a 4- to 5-inch reduction would mean an additional 52 acre-ft or 0.7 area-inch available to streamflow. Before treatment, Castle Creek averaged 2 inches of streamflow annually. Entering figure 2 with 17 percent as the amount in openings, and 2 inches of streamflow, the increase predicted by this chart is also 0.7 inch.

When fitted to the timber stand structure, clearcutting in small patches is compatible with recommended silvicultural methods for mixed conifers (Alexander 1974). These small forest openings also improve wildlife habitat for such species as deer, elk (Reynolds 1966, Wallmo 1969), grouse (Martinka 1972), and turkey.[4]

Water Quality

Sediment quantities vary over time and by measurement point. The annual rate of sedimentation was almost double in Roosevelt Reservoir for the period 1911-25 (Eakin 1936) compared to 1911-46.[5]

Fire and loss of vegetation significantly increase sediment losses (Rich 1962). Location and type of measurements have influenced apparent sediment quantities. Sediment losses as the result of a severe fire on Workman Creek varied from a rate of 0.21 to 1,066 acre-ft per 100 mi^2, depending on where and how measurements were made.

It is possible to treat watersheds without a serious increase in sediment yields. The Workman Creek rain gage recorded the all-time Arizona record for 24-hour precipitation on September 4 and 5, 1970 (U. S. Department of Commerce 1970). The watersheds were under treatment, yet sediment losses were relatively light on North Fork watershed. There was no apparent sediment loss measured at the mouth of the South Fork watershed.

Although it is evident that timber harvesting and the accompanying road construction can increase sediment production, they are insignificant in comparison to nature's destructive

[4]*Scott, Virgil E., and Erwin L. Boeker. Ecology of Merriam's wild turkey on the Fort Apache Indian Reservation. (Unpublished manuscript by Fish & Wildlife Service, U. S. Department of the Interior, on file at the Forestry Hydrology Laboratory, Rocky Mountain Forest and Range Experiment Station, Tempe, Arizona.)*

[5]*Salt River Water Users' Association. Chart titled "Combined flow of Salt and Verde Rivers." 1971.*

forces such as fire and thunderstorms. In the mixed conifer type, however, the ability of watersheds to revegetate makes major erosion events very temporary occurrences.

Implications

Although the mixed conifer areas of Arizona make up approximately 0.4 percent of the total land area, they contribute 6 percent of the State's water yield. A maximum of 290,000 acres in the mixed conifer could be treated. (At least 29,000 acres are in wilderness and primitive areas, or other land classifications that restrict logging.) Intensive forest management on this maximum area would significantly increase annual water yield. Intensive management is defined here as a patchcutting scheme with openings three to eight tree heights in width, with one-sixth of the area harvested each cutting cycle (approximately 20 years). After half the 120-year rotation age is reached, half the area will have been logged; one-sixth will be in recently cleared patches, one-sixth in 20-year-old reproduction, and one-sixth in 40-year-old pole stands. Each of these areas would be effective to some degree in reducing evapotranspiration and increasing snow accumulation; their effectiveness decreases with height of the new trees, however.

The total area of "effective" clearings would be at least 30 percent. Average runoff for the mixed conifer type is estimated at 4.7 inches (Forsling 1960). From figure 2, the estimated increase is 1½ area inches, which would increase total annual streamflow in Arizona by 1.8 percent, or about 36,500 acre-ft—12 billion gallons.

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Appendix

Workman Creek

These mixed conifer watersheds, on the Sierra Ancha Experimental Forest about 50 miles north of Globe, were calibrated and ready for treatments by 1954. Elevations vary between 6,590 and 7,700 ft for the bowllike basin that drains to the West. Each of the three watersheds—North Fork 248 acres, Middle Fork 521 acres, and South Fork 318 acres—supports a perennial stream.

Surface soils are of loam to clay loam texture, subsoils vary in texture from clay loams to clay. Infiltration rates are high near the soil surface and diminish with depth to extremely low rates below 12 inches.[6] Soil depth varies from a few inches to more than 15 ft. The watersheds are underlain by quartzite rock that has been intruded by diabase and basalt. Most formations are level. Average annual precipitation is just over 32 inches; streamflow prior to treatment had averaged from 3.19 to 3.42 inches for the three watersheds.

Winter precipitation, October through May, has averaged 66 percent of the annual total.

The forest vegetation on the Workman Creek watersheds is dominantly ponderosa pine, Douglas-fir, white fir, and Gambel oak. Proportions of the most abundant trees on the three watersheds prior to treatment were:

	North Fork	Middle Fork	South Fork
		(Percent)	
Ponderosa pine	52.2	46.4	59.4
White fir	20.1	20.2	25.5
Douglas-fir	4.1	10.1	5.8
Gambel oak	22.2	21.8	8.0
Other	1.4	1.5	1.3

Arizona alder and bigtooth maple are found adjacent to streams and seeps. Arizona walnut and quaking aspen are found sparingly; New-Mexican locust, found as a part of the understory, is often first to occupy the site when released by overstory removal.

North Fork riparian cut.—On the North Fork of Workman Creek watershed, we tested treatments intended to approach maximum water yield. The forest vegetation was converted to grass in four steps. The first step was to cut and poison all broad-leaved trees on wet sites along the stream channel. The Arizona alder and bigtooth maple adjacent to streams, springs, and seeps were cut during August 1953. Stumps were treated to prevent sprouting. The cut included 158 alders varying in diameter from 1 to 33 inches and 946 maples varying from 1 to 11 inches. The total basal area of these trees was approximately 0.6 percent of the total basal area of trees on the 248-acre watershed.

Annual water yields did not increase significantly following the removal of broad-leaved trees. Since riparian trees are deciduous, the streamflow was tested to determine whether their removal affected growing season water yield. The posttreatment years were not significantly different from the pretreatments years. Also, removal of the riparian trees did not change diurnal fluctuations of streamflow.

North Fork moist-site cut.—In the second treatment on North Fork all trees (mainly Douglas-fir and white fir) growing on moist sites (about 80 acres) were removed in fall of 1958 and replaced with perennial grass.

A break in topography between the steeper, moist slopes extending up from the stream channel and the flatter, dry slopes above the moist-site areas delineated the area for clearing in many places. Where topography did not determine the boundary, the area was considered moist-site wherever white fir and

[6] *Barret, Thomas W. Final report, Cooperative Agreemnt No. 16-68, Line Proj. FS-RM-1606, 319 p. 1970. On file at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

Douglas-fir stems 4 inches and larger made up more than 50 percent of the forest stand. Moist-site vegetation was found along both sides of the main stream channel and two contributing forks in the upper reaches of the watershed.

Trees larger than 10 inches were cut and removed to the sawmill. Smaller trees were pushed over with a bulldozer. Unmerchantable material was piled into windrows for burning. Most of the forest litter and debris was also pushed into slash piles, leaving a good seedbed for perennial grasses between the windrows.

Ground between the slash piles was seeded to a mixture of 40 percent slender wheatgrass (*Agropyron trachycaulum* (Link) Malte), 40 percent Kentucky bluegrass (*Poa pratensis* L.) and 20 percent orchardgrass (*Dactylis glomerata* L.) at the rate of 10 pounds per acre. Redtop (*Agrostis alba* L.) was planted along stream channels and seeps at the rate of 10 pounds per acre. Slash was burned in March 1959. In most of the slash piles, material smaller than 6 inches d.b.h. was consumed. Larger material was charred but not completely consumed.

Subsequent streamflow measurements have shown statistically significant water yield increases, and also a significant difference in pre- and posttreatment regression coefficients.

The different regression coefficients for the two periods indicate a fairly consistent yield increase for individual years that averages 45 percent higher than expected without treatment. Increases were smallest during the years of lowest runoff, larger during the years of higher streamflow.

North Fork dry-site cut.—The third treatment on North Fork replaced the merchantable tree area (ponderosa pine) on dry sites with grass. One hundred acres of merchantable ponderosa pine timber were harvested between September 1966 and June 1968. In December 1969 the remaining standing trees and slash accumulations were burned. The area was then seeded to the same grass mixture used for the moist-site area.

Streamflow measurements indicate additional water yield increases, as a result of the dry-site cut alone, varying from 15 percent when yields are 1 inch, to 38 percent at 3.0 inches, and 56 percent when the check watershed yields 7.0 inches. Comparing total yields after both the moist-site and dry-site cut indicates water yield increases varying from 72 percent at 1 inch, to 99 percent at 3.0 inches, and 110 percent when the check watershed yields 7.0 inches.

Covariance analysis for average conditions indicates a 45 percent increase for the moist-site cut, another 34 percent increase for the dry-site cut, and 96 percent increase for the two cuts combined.

South Fork selection harvest.—South Fork of Workman Creek, the other treatable watershed, was first managed for production of high-quality timber to determine the effect of individual-tree-selection harvesting on water yields and sedimentation.

The timber management cut was started in June 1953 and completed in November 1955. The gross volume marked for cutting was 3 million fbm (board ft), and the net volume after allowance for defect was almost exactly 2 million fbm. This harvest removed approximately 46 percent of the merchantable timber (conifers 12 inches and over). Basal area of trees 1 inch and over was reduced 24 percent. Logging damage, access roads, and skid trails reduced basal area by 6 percent.

Stand improvement work completed during 1956 consisted of poisoning undesirable trees with ammate. In small areas of pine infested with dwarf mistletoe, all trees were poisoned. Larger areas of infestation were isolated by poisoning a 60-ft border around the infestation. Gambel oak and New-Mexican locust which overtopped pine reproduction were also poisoned. In addition, where the composition was a mixture of pine and fir, firs were poisoned to favor growth and reproduction of pine. This improvement work reduced the basal area on the watershed by 6 percent. Slash was piled and burned along the main access roads. Roads, skid trails, and landing areas were subsequently seeded to perennial grass.

On July 6, 1957, a wildfire burned 60 acres of the upper southeast portion of the watershed. The fire burned the most level part of the South Fork watershed where stream channels are not well defined and where there is no perennial streamflow. The fire destroyed about 5,400 ft^2 of basal area on the 60 acres, or about 9 percent of the original basal area on the entire watershed. Thus, total basal area was reduced 45 percent by logging, road construction, improvement measures, and fire.

Annual water yields did not increase significantly when compared with yields from the control watershed. Water yields increased 4 or 5 percent 10 out of the 13 years, but this increase was not statistically significant.

South Fork conversion cut.—The second treatment was the transition of the entire South Fork watershed to ponderosa pine with 40 ft^2 basal area per acre. The timber harvest was started in late September 1966 and finished in June 1968. All merchantable timber was removed from the ponderosa pine area. Areas of dominantly white fir and Douglas-fir were cleared. Pine seedlings were planted in these cleared areas and in the burn area. The goal is to achieve a stocking level of 40 ft^2 of basal area per acre, all in ponderosa pine. In the meantime, we are collecting data on the effects of removing forest vegetation on water and sediment yield. In the future, data will be gathered on the effects of reforestation on water and sediment production.

The water yield results from South Fork almost exactly parallel the results from the combined moist- and dry-site cuts on North Fork. Water yield increases, when compared to the control Middle Fork watershed, vary from 185 percent when the control watershed yields 1.0 inch to 209 percent at 3.0 inches and 241 percent at 7.0 inches. Covariance analysis at average conditions indicates an increase of 111 percent, which compares favorably with the 96 percent for the North Fork watershed.

Castle Creek

The study area includes two watersheds, East Fork (1,163 acres) and West Fork (900 acres), in the Apache National Forest about 20 miles south of Alpine, Arizona. They drain into the San Francisco River, a tributary of the Gila. The western boundaries are adjacent to the Black River, a tributary of the Salt. Consequently, these watersheds should be representative of both the Gila and Salt River headwater areas. Elevations vary from 7,835 to 8,580 ft. The topography is relatively flat; slopes average about 12 percent and the watersheds have been described as an easy logging chance. The town of Alpine, at almost exactly the same elevation as Castle Creek, has an average temperature of 43.3°F, with 250 days with a minimum of 32°F or below, and 15 days with a minimum of 0°F or below. Freezing temperatures have been recorded every month of the year.

Castle Creek is predominately ponderosa pine, but is immediately adjacent to the extensive mixed conifer stand in the White Mountains of eastern Arizona. Because of its climatologic and hydrologic similarity to the mixed conifer, and because of its dissimilarity in stand characteristics to much of the porderosa pine in Arizona, we have considered it in our analyses as mixed conifer.

The watersheds were selected and 120° V-notch weirs were installed in 1955 to measure water yields. A systematic sampling of the two watersheds provided the following average measurements:

	West Fork	East Fork
Size (acres)	900	1,163
Aspect (direction, average of plots)	S43°E	N14°W
Slope (average of all measured points, percent)	12.6	13.8
Forage production (pounds per acre)	78.2	119.8
Litter (pounds per acre)	33,177	31,085
Soil mantle depth (ft)	2.6	2.8
Forest stand volume:		
(fbm per acre)	11,060	10,680
(ft^3 per acre)	2,723	2,139
Basal area (ft^2 of all trees 1 inch and over)	135	122

Precipitation at Castle Creek for the period 1957-73 averaged 26 inches; 54 percent occurred between October 1 and May 31. Maximum annual precipitation (37 inches) fell during water year 1973; the minimum (21 inches) occurred during 1970. The maximum monthly precipitation (11.4 inches) fell in October 1972. Three months during the 17-year period received no precipitation. August, the highest month, received 16 percent of the average annual total, and May, the lowest month, received 2.4 percent. Precipitation in May and June, the low point of the year, averaged only 6.1 percent of the annual total.

The treatment applied to the 900-acre West Fork of Castle Creek was a commercial timber harvest that placed five-sixths of the watershed in the best growing condition possible for the existing forest stand. It removed (1) poor risk and overmature trees, (2) mature trees where necessary to release needed age classes, (3) trees that overtopped or crowded residual crop trees, (4) poorly formed and other poor classes of trees, (5) damaged trees, and (6) all trees infected with dwarf mistletoe.

The forest on one-sixth of the watershed was clearcut in blocks fitted to existing stands of overmature and unneeded tree classes. The clearcut blocks were treated to obtain natural regeneration as a start toward even-aged management. Some planting was necessary to insure full stocking in these blocks.

The objective of the treatment on Castle Creek was to apply an improved type of timber harvest and subsequent management to obtain data useful in both timber and watershed management; data would be intermediate between the high and low possible threshold values obtained at Workman Creek. It was anticipated that water yield increases would be part way between those after the individual-tree-selection harvest (no significant increase), and the treatment where forest vegetation was removed and replaced by grass (a large gain).

Streamflow for the East Fork control watershed averaged 2.9 inches during the 10-year calibration period, and 3.6 inches during the first 7 years of the treatment period. On the West Fork watershed, streamflow averaged 2.0 inches during the pretreatment 10 years and 3.1 inches the first 7 years of the treatment period. Streamflow has varied from almost zero—0.03 inch from West Fork and 0.06 inch from East Fork during the 1955-56 water year—to 10.4 inches from West Fork and 13.8 inches from East Fork during the 1972-73 water year. Winter runoff has always ceased before the summer rains. More than 80 percent of the annual streamflow is yielded during February-April. June-September accounted for an average of only 8 percent of annual streamflow from West Fork and 7 percent from East Fork.

Seven years of data indicate a significant increase in annual water yields from West Fork—from more than 0.35 inch when the control watershed yields 0.5 inch annual runoff to more than 1.55 inches when the control watershed yields 13.0 inches annual runoff.

Willow-Thomas Creek

These experimental watersheds include East Fork of Willow Creek, 490 acres; West Fork of Willow Creek, 290 acres; North Fork of Thomas Creek, 440 acres; and South Fork of Thomas Creek, 545 acres. The elevations vary between 8,600 and 9,200 ft. Precipitation since 1959 has averaged 28.8 inches annually, and has varied from 20 to 43 inches. About 50 percent of the annual precipitation falls during the 8 winter months—October through May—and 50 percent during the 4 summer months—June through September.

The forest vegetation includes eight species. Composition of the forest (trees 7.0 inches in diameter and above) on the Willow Creek watersheds is:

	East Fork	West Fork
	(Percent)	
Engelmann spruce	21.7	24.1
Blue spruce	2.0	.1
Douglas-fir	25.7	19.9
White fir	6.6	7.8
Corkbark fir	2.6	9.0
Ponderosa pine	5.9	4.8
Southwestern white pine	3.3	1.8
Quaking aspen	32.2	32.5

East Willow Creek was a second test of the effects of a practical type of timber management on water and sediment yields. The treatment, completed September 30, 1972, was silviculturally fitted to the existing forest stand on the 490-acre watershed. Some portions of the area were selectively harvested, while other portions were harvested by the overstory removal method, based on a 10-inch-diameter marking guide. Results will be available after 4 or 5 years of posttreatment measurements.

South Thomas Creek will be treated in 1976. The treatment selected will depend on a complete benefit-cost analysis of several alternatives. Each alternative will have a specific management goal, and available data on esthetics, wildlife, water, timber, range forage, and erosion will be considered in the evaluation. Results from this treatment will be used to evaluate the various resource response models that were the source of inputs to the benefit-cost analysis. Where models do not exist, pretreatment and posttreatment data will be used to build simulation models.

Rich, Lowell R., and J. R. Thompson.
1974. Watershed management in Arizona's mixed conifer forests: The status of our knowledge. USDA For. Serv. Res. Pap. RM-130, 15 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Removing mixed conifer forest vegetation has increased water yields approximately in proportion to the percent of the area in cleared openings. Most of the yield increase can be accounted for by the reduction in evapotranspiration. Reduced soil-moisture deficit and increased snow accumulation and melt rates in the cut openings contribute to these increases. When fitted to the timber-stand structure, patchcutting is (1) compatible with recommended mixed conifer silviculture, (2) beneficial to wildlife, and (3) esthetically pleasing. Although mixed conifer areas make up only 0.4 percent of the total land area of Arizona, they contribute 6 percent of the State's water yield. Intensive management of these forest lands could increase annual streamflow 36,500 acre-feet per year—roughly 12 billion gallons of water per year.
Keywords: Water yield improvement, mixed conifer, sediment yield.

Rich, Lowell R., and J. R. Thompson.
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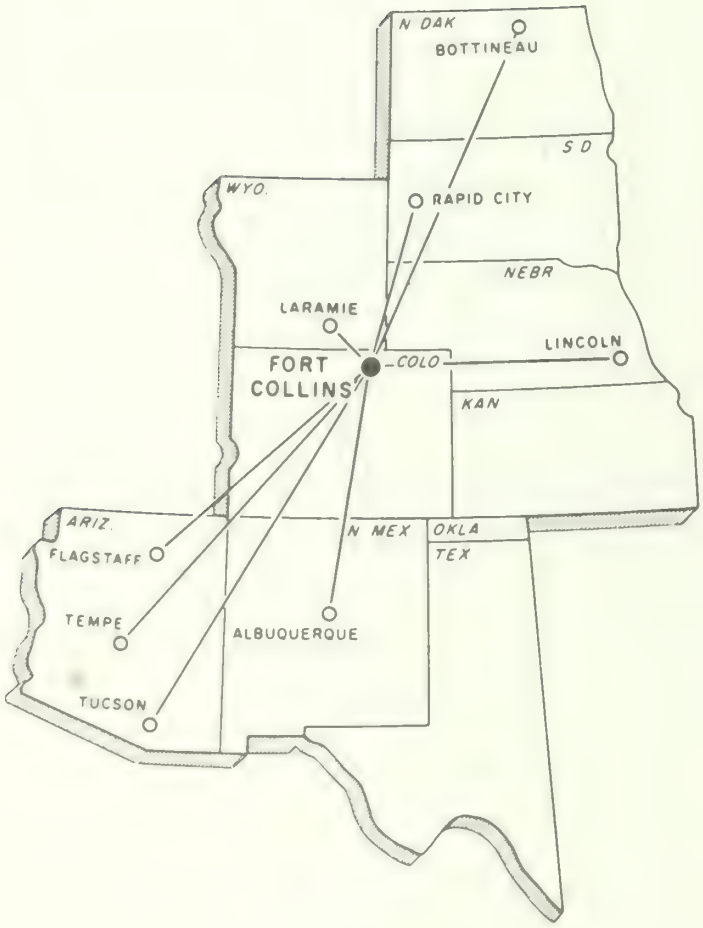
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Development of Spruce-Fir Stands Following Spruce Beetle Outbreaks

J. M. Schmid and T. E. Hinds

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USDA Forest Service
Research Paper RM-131

December 1974

Rocky Mountain Forest and
Range Experiment Station

Forest Service

U.S. Department of Agriculture

Fort Collins, Colorado 80521

Abstract

Logged and unlogged stands of Engelmann spruce-subalpine fir were evaluated in spruce beetle outbreak areas infested about 15, 25, 50, and 100 years ago. Seedling regeneration was generally adequate except in heavily logged areas, although seedlings were often damaged, apparently by animals. Species composition was dramatically altered in favor of fir in the unlogged spruce-fir type. In the overstory, fir may predominate for many years but eventually the spruce will replace it. When the forest reaches a basal area of 150 to 200+ ft^2 per acre in predominantly large spruce, the potential for spruce beetle outbreaks increases. Changes in species composition with different intensities of beetle infestations and over several centuries are hypothesized.

Keywords: *Picea engelmannii*, *Abies lasiocarpa*, *Dendroctonus rufipennis*, insect outbreaks, forest succession.

USDA Forest Service
Research Paper RM-131

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Development of Spruce-Fir Stands Following Spruce Beetle Outbreaks

J. M. Schmid, Principal Entomologist,
and
T. E. Hinds, Principal Plant Pathologist
Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University.*

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Development of Spruce-Fir Stands Following Spruce Beetle Outbreaks

J. M. Schmid and T. E. Hinds

Spruce-fir (*Picea engelmannii* Parry and *Abies lasiocarpa* (Hooker) Nutt., respectively) stands in the Rocky Mountains have periodically been ravaged by the spruce beetle (*Dendroctonus rufipennis* (Kirby)). Beetle infestations are usually in stands composed of older, larger diameter trees. When trees within these stands are blown down either individually, in scattered groups, or complete stands—as frequently happens—resident spruce beetle populations infest the windfallen spruce and may multiply to outbreak proportions. If an outbreak develops, the surrounding trees and adjacent stands may suffer varying degrees of mortality. The most extraordinary and damaging outbreak documented in recent times, decimated spruce stands in the White River area in Colorado during the 1940's (Wygant 1958).

Forest managers faced with a beetle outbreak have two basic alternatives: (1) attempt to control the outbreak and prevent further mortality, or (2) let the outbreak run its course. In the past 30 years, decisions have generally been to attempt to control the outbreaks through logging, trap trees, chemical methods, or a combination of these methods. Cold winter temperatures and woodpeckers aided control efforts in some instances. Few outbreaks ran their course without control measures being instigated.

Evidence of man's control activities, primarily logging in the infested spruce stands, has been obvious. Large openings, piles of logging residuals, scarred trees, and absence of adequate tree reproduction, have been observed by foresters and others alike. Their concern over the appearance of logged areas and the costs and values involved has led them to ask "Wouldn't it have been better to let the outbreak run its course?" This Paper attempts to answer that question by evaluating the structure, stocking, growth, and species composition in logged and unlogged spruce-fir stands formerly infested by spruce beetles.

Methods

Sampling areas were selected within four old outbreaks (fig. 1). Selection of a sampling area

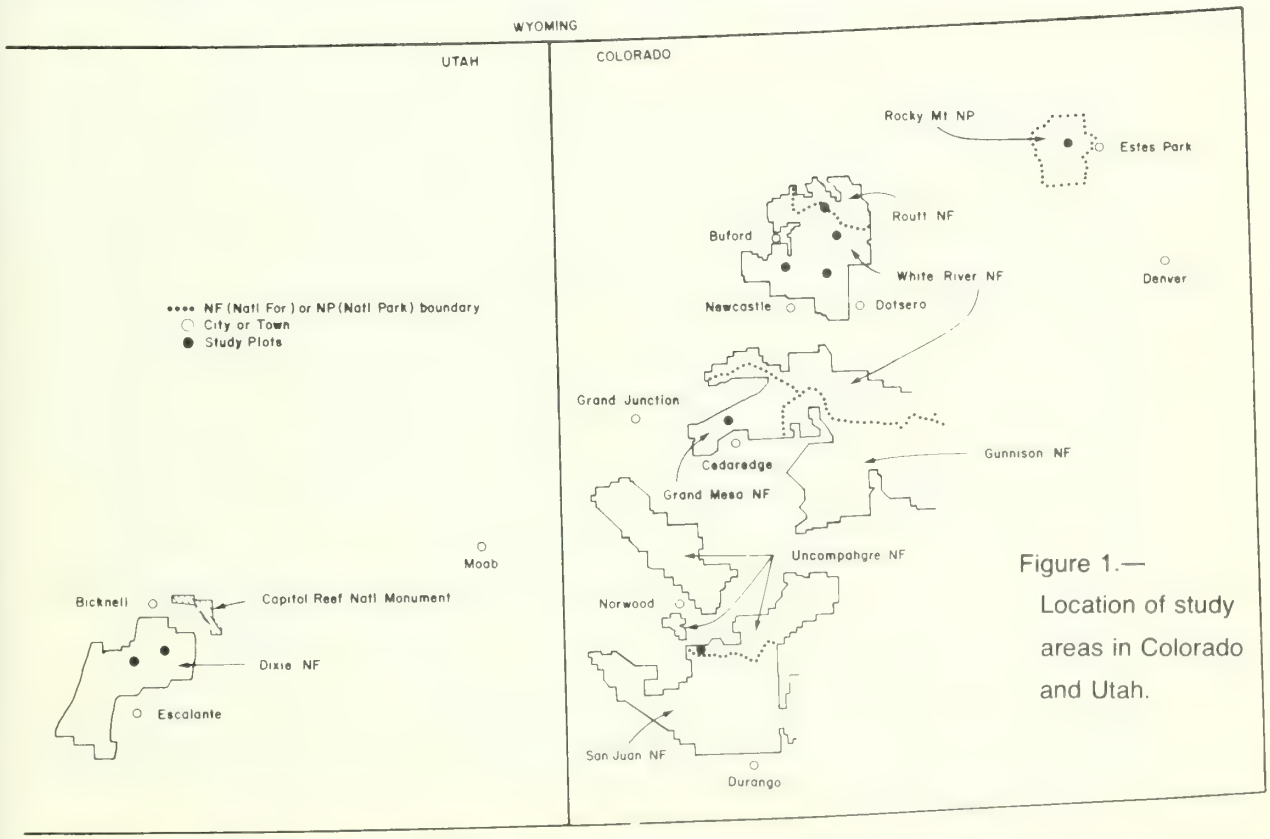

Figure 1.—Location of study areas in Colorado and Utah.

was based on: (1) dated records of an outbreak(s), and (2) evidence of logging. Most locations were visited prior to the actual sampling to acquaint us with the former outbreak area and to locate "typical" logged and unlogged sampling sites. Both the sampling sites and the number of sample plots were arbitrarily selected. A stand in Rocky Mountain National Park not subjected to known outbreaks or logging activity but with an endemic spruce beetle population was also sampled.

A series of 0.1 acre (0.04 ha) circular temporary plots was established in each old outbreak. Generally, 10 plots were established in a specific area of the outbreak. At Ripple Creek Pass, near Buford, Colorado, less than 10 were taken because permanent plots established in 1951 were used, and sites in the logged area differed. Ten previously established plots were also used near the Rio Blanco Ranch, White River National Forest.

Temporary plots were located 2 chains (40 m) apart on a compass line. If more than 25 percent of a plot consisted of herbaceous vegetation and it was judged to have existed as such prior to the outbreak, the plot was then reestablished further along the compass line where its entire area occurred on a previously forested site. In some areas, the stands consisted of small patches or strips so that 10 successive plots could not be taken along one line. The compass line was then offset 2 or 3 chains (40-60 m) and returned on a parallel course.

All live trees greater than 3 inches (7.6 cm) in height were recorded by species as follows:

Small seedlings—3.0 inches (7.6 cm) to 2 ft (0.6 m) in height.
Large seedlings—2 ft (0.6 m) high to 1.5 inches (3.6 cm) d.b.h. (diameter at breast height, approximately 4.5 ft or 1.4 m).
Saplings—1.6 (4.1 cm) to 2.5 inches (6.4 cm) d.b.h.
Pole-sawtimber—2.6 inches (6.6 cm) d.b.h. and larger measured to the nearest 0.1 inch (0.25 cm).

Seedlings and saplings were classified as healthy or damaged (fig. 2). Healthy trees had no obvious defects, while damaged trees were either deformed or sparsely foliated. Crown classes were assigned to trees 2.6 inches (6.6 cm) d.b.h. and larger.

One seedling of each species in each category was collected from each plot. Age, height, and diameter were determined later in the laboratory. One sapling in each species was cut after estimating its height, and a cross section was removed for aging in the laboratory. Increment cores were removed from trees of various diameters and later measured for annual growth to the nearest 0.001 inch (0.025 mm) in the laboratory. Heights were measured for several trees of different crown classes.

All dead trees were recorded by species and d.b.h., including downed trees and their cause of felling: knocked over by other falling trees, windthrown, or butt rot. The d.b.h. of cut trees was estimated from the diameter of the stump.

Basal area, which was used as an index of species composition, was computed for trees 2.6 inches (6.6 cm) d.b.h. and larger. For increases in basal area (growth) on the unlogged Rio Blanco and Ripple Creek Pass areas, basal area was computed for trees 5.0 inches (12.7 cm) d.b.h. and larger because when these permanent sample plots were established, 5.0 (12.7 cm) was the lowest d.b.h. recorded.

History and Description of The Study Areas

Grand Mesa, Colorado

Grand Mesa is a high-elevation (10,000 ft or 3,050 m) mesa with escarpments along some parts of the rim. Broad benches exist below the rims, and drainages from these benches form natural lakes or have been dammed to form artificial lakes. Spruce and fir predominate in the forested parts of the mesa and upper benches, and form patches of forest interspersed with meadowland. Meadowland is more common on the mesa, and is grazed by cattle.

Sudworth (1898b) reported 25 to 40 percent of the mature spruce on the mesa was killed around 1875 by spruce beetles. Another infestation in the 1940's killed the larger spruce.[2] During this latter outbreak, over 50 percent of the merchantable volume was killed but this included less than half the number of live trees (thus indicating the preference of the beetle for larger trees). Numerous pole-sized trees (5 to 9 inches d.b.h.) remained. Salvage logging was done during and after the 1940's outbreak, but not the 1875 infestation. The Scales Lake and Flowing Park Reservoir plots were on the mesa, while the Big Creek Reservoir plots were on the benches below the rim. According to Struble's 1944 report, the Scales Lake area was lightly infested while the Flowing Park and Big Creek Reservoir areas were heavily infested.

[2]*Struble, G. R. 1944. The Engelmann spruce beetle–a progress report of 1944 studies on the Grand Mesa National Forest, Colorado. 25 p. Unpubl. rep. on file, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

Figure 2.— Fir seedlings were either healthy (A) or damaged (B).

Boulder Top—Aquarius Plateau, Utah

The Aquarius Plateau is a basaltic extrusion which culminates in a high mesa (11,000 ft or 3,350 m), commonly called the Boulder Top. The Boulder Top Mesa is bounded by escarpments on the north and east but grades gradually into the rest of the Plateau to the southwest.

Spruce, fir, and aspen (*Populus tremuloides* Michx.) are mixed in the spruce-fir type of the Plateau, while on the Boulder Top, spruce exists in pure stands. Sites on the Boulder Top are poor and very rocky. The spruce-fir at lower elevations is less interspersed with grasslands, while the Boulder Top is predominantly grassland with only small patches of pure spruce.

Between 1916 and 1918, an infestation began that eventually killed nearly all the large spruce on the Aquarius Plateau before it subsided in 1928-29 (Mielke 1950). Local ranchers cut small numbers of dead trees for corral poles, fencing, and house logs almost immediately after the trees were killed. Starting about 1935, larger volumes of smaller trees were annually removed for mine props (Mielke 1950) and this was continuing in 1971. Salvage logging for saw logs began in 1944 and was continuing in 1971 on a limited basis. Initially, cutting started below the Boulder Top, moved to the Boulder Top in 1948, and was continuing in 1971 on its eastern edge. Early skidding was done with horses; skidding in 1971 used mechanized equipment.

Plots on the Boulder Top were located on the east side in pure spruce logged with mechanized equipment. Additional plots on the Aquarius Plateau but off the Boulder Top were established near Roundy Reservoir in a mixed stand logged with horses.

White River Plateau, Colorado

The White River Plateau, composed of several mesas, varies between 10,000 and 11,500 ft (3,050 and 3,505 m) in elevation and is subdivided by several drainages. Spruce and fir form small patches or irregular stands interspersed with meadows. The forested areas are more predominant on slopes or ridges angling downward from the Plateau. Lodgepole pine (*Pinus contorta* Dougl.) and aspen may be mixed with the spruce and fir on these lower slopes or ridges.

A spruce beetle outbreak occurred on the Plateau around 1875 (Sudworth 1898a). Another infestation began in 1939 and continually expanded during the 1940's (Massey and Wygant 1954) from one part of the Plateau across canyons to other parts until eventually, nearly all spruce 8 inches (20 cm) d.b.h. or larger was killed. In some areas, a few scattered, individual spruce trees up to 16 inches (40.6 cm) d.b.h. survived. Salvage logging was initiated for pulpwood and saw logs in several locations in the late 1940's.

Plots near Hiner Spring (near Newcastle) were in the western part of the Plateau, while the Deep Lake plots were on the southeastern part. Approximately 50,000 cords (128,000 m^3) of timber were cut in the general vicinity of the logged plots near Newcastle, but stands were not cut uniformly. Trees were cut only 1 to 3 chains (20 to 60 m) in from the edge of the stand. For unknown reasons, some trees were cut while others of equal accessibility and soundness were left. Logged plots near Deep Lake were in an area where 200,000 cords (510,000 m^3) of timber were removed. Full-length trees were skidded by mechanized equipment. Plots near Rio Blanco Ranch and Ripple Creek Pass were on a north-facing slope and a ridge, respectively. The Rio Blanco site was predominantly lodgepole pine-Engelmann spruce prior to the infestation. On the logged plots at Ripple Creek Pass, only the larger dead trees were logged and these were skidded with horses. One logged site was quite wet.

Lone Cone, Colorado

This area was in a valley between two ridges at an elevation of 8,500 ft (2,900 m), and differed from most of the previous study areas in that very few meadows existed within the spruce-fir forest. It also differed from the other areas because the infestation was detected and the infested trees logged or chemically treated before the infestation became extensive. Logged areas were clearcut; full-length trees were skidded with mechanized equipment.

Rocky Mountain National Park, Colorado

This spruce-fir area was on a north-facing slope at an elevation of 10,300 ft (3,140 m). On some wet sites, running water was probably available in early summer. The area was chosen because it was a mature stand that never had been logged. Also, spruce beetles had killed or are currently killing scattered, large-diameter trees, but an extensive outbreak has not occurred in the last 100 years.

Results and Discussion

Number of Live Trees

The average number of seedlings, saplings, and pole-sawtimber trees varied greatly from area to area within and between infestations.

Fir seedlings generally outnumbered spruce seedlings in all areas except on one logged site at Ripple Creek Pass and in the pure spruce of Boulder Top (table 1). On some sites, fir seedlings outnumbered spruce 10:1, while on other sites their numbers were nearly equal. Fir saplings outnumbered spruce saplings on most of the White River areas and in Rocky Mountain National Park; elsewhere spruce saplings were as numerous or more abundant than fir (table 1). In trees over 2.6 inches d.b.h., spruce was generally less numerous than fir on the White River but more numerous on the other areas (table 1).

Differences in the number of live trees on the unlogged and logged plots on the Lone Cone and White River areas resulted from several factors, but logging was probably the primary reason. Logging can destroy 50 to 70 percent of the trees less than 1 ft tall (USDA Forest Service 1948) or 50 percent of the advanced reproduction (Alexander 1963). However, as Alexander (1963) notes, the amount of reproduction destroyed is greatest where logging activity is greatest. Where logging was heavy at Lone Cone and Deep Lake on the White River, herbaceous vegetation now appears to preclude natural establishment of seedlings. Roe et al. (1970) noted that shrubs and other lower growing vegetation may occupy a site after a disturbance (insect outbreak, clearcut) and preclude the establishment of tree species for many years unless seed falls soon after the disturbance. Elsewhere on the White River (Hiner Spring and Ripple Creek Pass) logging was not so destructive, perhaps because of less intensity. The Hiner Spring area, like Deep Lake, consisted of strips of timber separated by meadows, but considerably fewer beetle-killed trees were cut. Also, in the Hiner Spring area, trees were logged a few chains in from the edge and selected material was skidded with horses. Under this type of logging, damage was not nearly so severe as near Deep Lake, and consequently logged and unlogged plots had similar numbers of small seedlings.

Table 1.--Characteristics of study areas, by outbreak location, logging status, years since infestation(s), and average number per acre of seedlings, saplings, and trees 2.6 inches and larger d.b.h.

Outbreak location and logging status (L = Logged) (U = Unlogged)		Approximate years since infestation(s)	SEEDLINGS					SAPLINGS			TREES 2.6 INCHES D.B.H. AND LARGER		
			SPRUCE		FIR								
			<2 ft tall	2 ft tall-1.5 inches d.b.h.	<2 ft tall	2 ft tall-1.5 inches d.b.h.	Total	SPRUCE	FIR	TOTAL	SPRUCE	FIR	TOTAL
GRAND MESA													
Grand Mesa NF													
Scales Lakes	-U	100,25	141± 27	114± 20	417± 51	631± 88	1,303	52± 6	66± 14	118± 16	291±24	212±29	503±42
Big Creek Reservoir	-U	100,25	283± 56	81± 13	858±175	697±128	1,919	32± 6	95± 20	127± 19	144±18	268±26	412±32
Flowing Park Reservoir	-L	100,25	660±127	337± 58	948±145	433± 52	2,378	53± 8	16± 9	69± 11	226±36	84±14	310±32
AQUARIUS PLATEAU													
Dixie NF													
Boulder Top	-U	50	119± 34	211± 30	1± 1	1± 1	332	110±19	0	110± 19	187±23	1± 1	188±22
Boulder Top	-L	50	407±115	361± 65	2± 1	0± 0	770	27± 6	0	27± 6	98±15	0	98±15
Roundy Reservoir	-L	50	59± 10	323± 62	59± 17	111± 45	[1]638	80±17	16± 7	[1]148± 25	265±42	21± 9	[1]365±35
WHITE RIVER PLATEAU													
White River NF													
Ripple Creek Pass	-U	100,25	354± 49	30± 30	529± 34	69± 69	982	47±14	99± 18	146± 22	54±16	248±37	302±39
Ripple Creek Pass	-L	100,25	110± 40	402± 61	28± 10	138± 39	678	67±14	50± 19	117± 27	55±19	155±26	210±31
Ripple Creek Pass	-L	100,25	107± 32	340± 43	155± 37	660±184	1,262	33± 2	142± 44	175± 43	35± 8	278±46	313±42
Mirror Lake	-U	100,25	95± 22	227± 57	301± 53	472±108	1,095	53±17	72± 14	125± 22	151±20	168±25	319±22
Hiner Spring	-L	100,25	13± 6	52± 10	102± 24	426±109	593	24± 5	70± 28	94± 30	179±26	116±28	295±46
Cliff Lake	-L	100,25	65± 14	222± 48	321±133	407± 70	1,015	42±12	65± 21	107± 28	130±18	152±34	282±40
Deep Lake	-U	100,25	47± 11	228± 37	[2]53± 25	325± 48	653	35± 8	94± 17	129± 16	46±14	222±33	268±38
Deep Lake	-L	100,25	8± 3	70± 15	[2]22± 7	74± 14	174	15± 5	10± 3	25± 4	19±10	35± 7	54±12
Deep Lake	-L	100,25	7± 4	41± 8	14± 6	256± 47	[2]318	7± 3	40± 7	[2]47± 9	25± 7	63±12	[2]88±16
Rio Blanco Ranch	-U	100,25	677±159	636±138	1,389±184	1,648±111	[2]4,386	46±15	111± 16	[2]157± 15	28± 9	175±19	[2]204±17
LONE CONE													
Uncompahgre NF													
Lone Cone	-U	15	258± 61	203± 33	418± 62	302± 41	1,181	40± 7	32± 11	72± 16	179±26	87±16	266±25
Lone Cone	-L	15	27± 8	71± 16	81± 22	116± 22	295	8± 3	6± 3	14± 5	12± 4	21± 5	33± 9
ROCKY MOUNTAIN NATIONAL PARK													
Hidden Valley	-U	--	189± 37	94± 13	637±122	606±117	1,526	4± 3	44± 11	48± 12	117±12	93±18	210±17

[1]Includes some aspen.
[2]Includes some lodgepole pine.

Although logging intensity was not as great at Ripple Creek Pass as at Deep Lake, logging, site, and competition of herbaceous vegetation influenced differences in the number of small seedlings on the logged and unlogged plots. Rapid growth of herbaceous vegetation after logging on the more moist sites (fig. 3) reduced successful establishment of seedlings. However, this dense herbaceous growth does not explain why the number of large seedlings is substantially less on unlogged plots. Since sites were noticeably different, this difference in seedlings might be a prime example of the variability in spruce stands suggested by Alexander (1971). It is also possible that seedlings in the logged area grew out of the smaller category in response to logging. If both categories of seedlings are combined, the differences between logged and unlogged areas are not so great.

The number of seedlings on the Boulder Top was considerably greater in the logged area than in the unlogged area (table 1). Trees 2.6 to 13 inches d.b.h. were generally more numerous on the unlogged plots than on logged plots, but for trees greater than 13 inches d.b.h. the situation was reversed. These differences—as well as just the number of trees—illustrate the effects of site, stand, and logging factors. The number of live trees (table 1) indicates a poor site, because tree numbers are substantially less than on areas of the White River even though the Aquarius Plateau was infested 25 years previously. The trees that survived the infestation are open grown, which reflects stand conditions, but could also account for differences in seedling numbers. Such trees would probably bear seed more often than trees grown in a dense stand and could therefore contribute seed after logging. The lower proportion of pole-sawtimber trees and the higher proportion of damaged seedlings on the logged plots evidences the influence of logging.

Seedlings near Roundy Reservoir (table 1) were more numerous than on the unlogged Boulder Top and slightly less numerous than on the logged Boulder Top. Logging partially accounts for these differences in two ways. First, salvage logging began in the 1940's near Roundy Reservoir with horses. This type of logging probably damaged the residual stand less, and when combined with a better site allowed greater numbers of pole-sawtimber trees to survive. In addition, the earlier logging aided establishment of seedlings which by now have grown into the large category. As the stand developed after logging, competition became greater and reduced survival of subsequent seedlings. Thus, the present number of small seedlings near Roundy Reservoir is less than on the Boulder Top, where logging is more recent and consequently less competition.

Seedlings near Scales Lake were less numerous than near Flowing Park Reservoir (table 1),

Figure 3.—Dense herbaceous vegetation inhibits seedling establishment—Logged site at Ripple Creek Pass.

but saplings and pole-sawtimber trees were more abundant. Intensity of the infestation and subsequent logging seem to account for these differences. Although Sudworth (1898b) indicates 25 to 49 percent of the stand on the mesa was killed, a substantial number of intermediate and perhaps codominant spruce remained to become the stand attacked by the beetle in the 1940's. Struble's report indicates that the area near Scales Lake was lightly infested, while the area near Flowing Park Reservoir was heavily infested. Since logging was used for control, logging was concentrated where the infestation was heaviest so that more pole-sawtimber trees were removed near Flowing Park Reservoir. This logging created favorable sites for seedlings, and subsequent seedfall from the remaining live trees established a greater number of seedlings in this area.

Seedling Damage

Damaged seedlings were found in all areas. Proportions ranged from 9 to 60 percent for fir and 5 to 45 percent for spruce on unlogged plots, and from 20 to 61 percent and 16 to 40 percent for fir and spruce, respectively, on logged plots. The percentage of damaged small seedlings of both species averaged about 10 percent less than for large seedlings. The percentage of damaged fir seedlings averaged about 8 percent more than spruce on unlogged plots, while on logged plots, about 25 percent more fir were damaged.

Although the differences in damaged seedlings on logged versus unlogged plots seems to suggest logging as a major injurious factor, the type of damage generally indicated that logging contributed only indirectly to damage.

Windfalls damaged some seedlings, either by stripping off branches or holding the seedling in a bent-over position so that its main vertical growth is not directly above its root system. Hinds et al. (1965) estimated that beetle-killed spruce fall at the rate of 1½ percent per year, so this type of damage can be expected to continue for at least another 30 years.

The most important damage factor appeared to be browsing, either by domestic livestock, elk (*Cervus canadensis* (Erxleben)), deer (*Odocoileus hemionus* (Rafinesque)), or small rodents. Most damaged seedlings had the terminal leader missing or deformed (fig. 2B). Frequently, when this leader was gone, a lateral shoot became the terminal. The seedling took on a broomed look, and while apparently healthy otherwise, became bushy and lost height growth.

Food is plentiful when the deer and elk inhabit the spruce-fir, so they probably account for little if any of the damage. Wallmo et al. (1972) reported practically no browsing of mule deer on Engelmann spruce and subalpine fir in logged and unlogged strips in Colorado. Kufeld (1973) indicates spruce and fir have negligible food value for elk.

Sheep and cattle are more probable causal agents because most of these infested areas were in their summer range on mesas consisting of stands of spruce-fir interspersed with meadows. The stands provide natural shade and cover for livestock between the meadows. Since herbaceous vegetation has increased after the White River outbreak (Yeager and Riordan 1953), the animals would tend to forage in the strips of forest as well as in the meadows. In addition, the herbaceous vegetation is apparently even more abundant in logged areas so that logging may indirectly account for some damaged seedlings because it creates more attractive forage areas. Where stands are more contiguous and occupy greater areas, thus inhibiting stock movements, perhaps the damage would be more attributable to elk, deer, small rodents, or freezing temperatures. Rabbits may be a factor in winter when they browse on leaders above the snowline. Both early and late frosts may also kill new growth.

The greater amount of damage to fir seedlings reduces the fir's advantage in succession of the stand. Since fir seedlings usually outnumber spruce, fir has a better chance of eventually dominating the overstory. The damage factor may compensate for the numerical advantage, and allow spruce to gain a height advantage.

It should be stressed that these damaged seedlings are generally alive but deformed. They have survived the mortality factors of young seedlings cited by Ronco (1961, 1970), but have incurred or are incurring damage by other factors. Our minimum size limit for seedlings placed most of them beyond the size Ronco considered, but the mortality factors he cited as well as others are killing seedlings smaller than our minimum. As no data are available upon which to predict the growth response of damaged seedlings, these damaged seedlings could easily recover and become mature trees if further damage is not incurred.

Stocking

The minimum stocking requirements for spruce-fir stands are 600 seedlings and saplings per acre of good form and vigor and free of defect before cutting (Alexander 1971); or 300 well-established and well-distributed

acceptable seedlings per acre or 150 saplings after cutting (Roe et al. 1970). Although our combined seedling category does not correspond exactly with Alexander's, the categories are similar enough so that the two logged Deep Lake sites, the logged Lone Cone, and unlogged Boulder Top sites are below or slightly above these minimum requirements (table 1). Considering the number of damaged or deformed seedlings found, stocking in these areas is well below minimum standards. Other areas averaging about 600 to 700 seedlings per acre (table 1) are only slightly above minimum standards when the damaged seedlings are subtracted from the totals. Since similar conditions may have prevailed in the 50- and 100-year-old beetle-killed stands, this light stocking including damaged seedlings may be adequate for new stands. This remains to be seen in the 25-year-old infestations, particularly those in unlogged or lightly logged areas.

Growth

Diameter growth at breast height of pole-sawtimber spruce and fir varied considerably between trees, plots, and areas. Trees in logged and unlogged areas increased in diameter following the beetle outbreak and/or logging as would be expected since the number of living trees was greatly reduced.

Increases in diameter of individual trees ranged from 0.02 to 0.35 inch per year, although the higher rates were not maintained for more than a few years. Diameter growth generally averaged between 0.5 and 1.5 inches for 10-year periods. A growth rate of less than 0.4 inch per 10 years should probably be considered as poor; 0.5 to 1.0 as average, 1.1 to 1.5 as good, and anything more than 1.5 per 10 years, excellent.

Two areas, Rio Blanco and Boulder Top (both unlogged), showed distinct differences in diameter growth prior to and after the beetle infestation. Diameter growth averaged less than 0.3 inch per 10 years for 2 decades prior to the beetle attack in the Rio Blanco area and averaged about 1 inch per 10 years for the 20 years following the outbreak. Similarly, diameter growth on the Boulder Top averaged less than 0.2 inch per 10 years for 30 years prior to the outbreak, and about 1 inch per 10 years for 40 years following the infestation.

Height growth of fir and spruce seedlings less than 2 ft tall ranged from 0.35 to 0.85 and 0.40 to 0.80 inch per year, respectively (table 2). Average height increment for both species was lowest on those sites with the larger basal areas of live trees. Average annual height increment was about equal for both species on the same sites. Thus, height growth of seedlings is promoted by outbreaks because it reduces competition from larger trees. Salvage logging,

Table 2.--Average height growth (inches per year) of fir and spruce seedlings less than 2 feet in height

Outbreak location and logging status (L = Logged) (U = Unlogged)		SPRUCE	FIR
GRAND MESA			
Grand Mesa NF			
Scales Lakes	-U	0.45	0.37
Big Creek Reservoir	-U	.48	.47
Flowing Park Reservoir	-L	.59	.42
AQUARIUS PLATEAU			
Dixie NF			
Boulder Top	-U	.53	([1])
Boulder Top	-L	.58	([1])
Roundy Reservoir	-L	.45	.49
WHITE RIVER PLATEAU			
White River NF			
Ripple Creek Pass	-U	.78	.47
Ripple Creek Pass	-L	.80	.85
Ripple Creek Pass	-L	.74	.64
Mirror Lake	-U	.60	.65
Hiner Spring	-L	.60	.57
Cliff Lake	-L	.64	.74
Deep Lake	-U	.58	.56
Deep Lake	-L	([1])	([1])
Deep Lake	-L	.81	.66
Rio Blanco Ranch	-U	.68	.64
LONE CONE			
Uncompahgre NF			
Lone Cone	-U	.40	.37
Lone Cone	-L	([1])	([1])
ROCKY MOUNTAIN NATIONAL PARK			
Hidden Valley	-U	.40	.35

[1]Species absent or numbers so low we did not remove seedlings.

however, did not generally influence height growth of the established seedling. Site also influenced height growth of seedlings, and compensated for increased competition from higher densities of seedlings. The Rio Blanco area with high average height growth and high seedling densities illustrates this case.

Age determinations of the seedlings less than 2 ft in height indicated more than 80 percent of the spruce seedlings in the four White River areas originated after the outbreak. Thus, even though an outbreak may kill over 99 percent of the dominant trees, a few trees remain to provide some seed for restocking.

BA (basal area) increased at the average rate of 0.35 and 1.2 ft^2 per acre per year on the unlogged Rio Blanco and Ripple Creek Pass areas, respectively. Assuming BA growth continued at these rates, it would take about another 335 and 150 years, respectively, to achieve the pre-outbreak BA values on these locations. This wide difference in projected recovery time reflects the destruction on the two sites; after the outbreak, the Rio Blanco area had only 40 trees per acre over 5.0 inches d.b.h. while the Ripple Creek Pass area had 148. The rate of BA growth should increase, so that time to achieve pre-outbreak values would be considerably less. Species composition complicates the BA picture, however. Both stands are now over 85 percent fir, so that if the stands do achieve prior BA values with the existing species composition, they would not be the same as existed prior to the outbreak. In addition, fir generally begin to die when they reach a d.b.h. of 15 to 18 inches (125 to 175 years) which would decrease the rate of BA increase and, consequently, lengthen the time to achieve pre-outbreak levels. To achieve those values with the same pre-outbreak percentage of spruce will require at least 300 years.

Species Composition

Spruce comprised 80 percent of the BA in the unlogged Lone Cone area while fir comprised 20 percent (table 3). Seedling composition was about 40 percent spruce and 60 percent fir (see table 1). On the logged area, fir comprised 79 percent of the BA while spruce was 21 percent. Seedling composition was about the same as on the unlogged area except for small seedlings, where numbers were too small to be significant. The infestation coupled with the logging altered the species composition and essentially reversed the most prevalent species from spruce to fir in pole-sawtimber trees.

The spruce component in stands on the White River changed dramatically. Prior to the outbreak, spruce comprised over 90 percent of the BA on the Ripple Creek Pass, Mirror Lake, and Deep Lake unlogged plots. After the outbreak, spruce comprised about 15, 50, and 15 percent of the BA respectively (table 3). On the logged plots, the percentage of spruce in the live BA was about 10 to 20, 50 to 70, and 20 for the same respective areas. Spruce comprised about 35, 30, and 45 percent of the seedlings on the unlogged plots (see table 1). The infestation altered the pole-sawtimber spruce component, but subsequent logging did not essentially change these percentages of spruce and fir. The effect of the infestation on the species composition of seedlings could not be determined. Logging coupled with the infestation appears not to have altered species composition in most cases, although the percentage of spruce seedlings was less on one logged area near Hiner Spring and greater on one area near Ripple Creek Pass. This was just the inverse of the percentage of spruce in the live BA for the respective areas.

Species composition on the Rio Blanco area of the White River differed from the other areas. Lodgepole pine and Engelmann spruce comprised essentially all of the BA prior to the outbreak, with lodgepole pine accounting for 60 percent. Now, lodgepole pine above 2.6 inches d.b.h. is essentially nonexistent, spruce comprises less than 10 percent of the BA, and fir accounts for the rest (table 3). Spruce comprises about 33 percent of the seedlings while fir accounts for the remaining percentage (see table 1). Since considerably less than 1 percent of the seedlings were lodgepole pine, their numbers were not separately indicated in table 1. The infestation dramatically altered species composition because lodgepole pine will probably disappear from the stand as it matures. This area also exemplifies an abnormal attack by the spruce beetle on lodgepole pine. The volume constitutes a substantial part of the 500 million fbm of pine destroyed by the beetle according to Massey and Wygant (1954).

Species composition did not change on the Boulder Top where before and after the outbreak, over 99 percent of the BA consists of spruce (table 3). Seedling composition on the Boulder Top also remains essentially pure spruce (see table 1). Neither the infestation nor logging affected the species composition in this area.

The Roundy Reservoir area had 74, 3, and 23 percent of the BA in spruce, fir, and aspen, respectively (table 3). Small seedlings were 48 percent spruce, 48 percent fir, and 4 percent aspen, while large seedlings were 62, 23, and 15 percent, respectively. Since pre-outbreak conditions are not known, changes in species composition, if they did occur, cannot be dis-

Table 3.--Average basal area (ft^2/acre) by size class

Outbreak location and logging status (U = Unlogged)		SPRUCE					FIR					
		2.6-4.9	5.0-9.0	9.1-20.9	21.0+	Total	2.6-4.9	5.0-9.0	9.1-20.9	21.0+	Total[1]	Total[1]
GRAND MESA												
Grand Mesa NF												
Scales Lakes	-U	9±1	27± 4	89· 6	7· 4	132	6±1	26±5	29· 5	0	61	193±25
Big Creek Reservoir	-U	3±1	13± 2	49· 8	2	67	8±2	27±3	53±14	0	88	162· 9
Flowing Park Reservoir	-L	6±1	19· 4	69±14	7· 4	101	1±0.3	9·2	32± 8	0	42	142±17
AQUARIUS PLATEAU												
Dixie NF												
Boulder Top	-U	5·1	16· 4	40± 5	0	61	0	·1	0	0	<1	62± 7
Boulder Top	-L	1·0.4	8· 2	48± 6	3	60	0	0	0	0	0	61± 7
Roundy Reservoir	-L	6±1	27±14	62· 8	0	95	1±0.3	1±1	3· 2	0	5	[2]129+11
WHITE RIVER PLATEAU												
White River NF												
Ripple Creek Pass	-U	2±1	5± 2	4± 3	0	11	8·1	23±4	41± 7	0	72	82·12
Ripple Creek Pass	-L	2·1	5± 4	2· 2	0	9	5±1	17±2	17± 6	0	39	49± 5
Ripple Creek Pass	-L	1·0.4	4± 2	0	0	5	9±2	23·4	37± 7	0	69	74±11
Mirror Lake	-U	4±1	11± 3	36· 7	0	51	4·1	18±3	28±10	0	50	101±12
Hiner Spring	-L	3±1	22· 4	40± 6	0	65	4±2	9±6	18· 5	0	31	97± 6
Cliff Lake	-L	3±1	12· 3	29· 4	0	44	5±2	13·3	25± 6	0	43	88± 9
Deep Lake	-U	2·1	4± 2	1· 1	0	7	8±1	24±5	16· 0.4	<1	48	57± 5
Deep Lake	-L	1±1	2± 1	0	0	3	1±0.3	3±1	7± 3	0	11	14±10
Deep Lake	-L	1±0.3	2± 1	1	0	4	2±0.5	3±1	9± 3	·1	14	22± 6
Rio Blanco Ranch	-U	1±0.6	1± 0.9	0	0	2	8±1	16±3	5· 2	0	29	[3]33· 4
LONE CONE												
Uncompahgre NF												
Lone Cone	-U	4±1	11± 3	92·11	36± 7	133	2±0.5	8±2	23± 3	0	33	167±10
Lone Cone	-L	0.3±0.2	2· 1	2± 1	0	4	0.3±0.2	2±2	14± 6	0	16	21± 6
ROCKY MOUNTAIN NATIONAL PARK												
Hidden Valley	-U	0.3±0.1	4± 1	99·13	68±14	171	3±0.6	7±1	25±10	3	38	209±24

[1]Some inconsistencies in total basal area and sum of the subtotals for spruce and fir due to rounding.
[2]Includes some aspen.
[3]Includes some lodgepole pine.

tinguished between the beetle or logging as causal factors. It appears that fir was becoming more numerous and aspen less so at the time of the outbreak. Logging may have stimulated aspen suckering and enhanced spruce seedling survival.

Near Scales Lake and Flowing Park Reservoir (Grand Mesa National Forest), about 70 percent of the BA was spruce, while fir accounted for the other 30 percent (table 3). Seedling composition on those areas was different; the unlogged Scales Lake area had about 15 to 25 percent spruce while the logged Flowing Park Reservoir area had 40 to 45 percent spruce (see table 1). Big Creek Reservoir area had nearly a 1:1 ratio in BA of spruce and fir, but spruce comprised only 10 to 25 percent of the seedlings. As on the Aquarius Plateau, the effect of the beetle or logging on species composition cannot be defined. Logging may have favorably influenced spruce seedling survival on the Mesa because the percentage of spruce was greater on the logged area.

All areas were covered by vegetation; none had expanses of bare soil. Logged stands of the Lone Cone and White River areas and some unlogged White River stands had especially dense growths of *Mertensia, Lupinus, Delphinium,*

Ranunculus, *Arctostaphylos*, and *Heracleum* (fig. 4). This dense vegetation competes with existing seedlings and prevents successful establishment of postoutbreak or postlogging seedlings.

Species composition of trees in spruce-fir stands could be altered by the following factors: (1) composition of the stand at the time of the outbreak, (2) intensity of the outbreak (number of trees killed per acre), (3) size of the outbreak (number of acres), and (4) time and intensity of logging.

If the stand is essentially pure spruce, then neither beetles nor logging would alter the spruce component unless the intensity of logging is so great as to convert the stand to herbaceous vegetation.

If the stand is dominantly spruce-fir (as in the central Rockies) or spruce-lodgepole pine, then various interactions are possible between the stand, outbreak and logging:

1. A spruce-fir stand sustaining an intensive attack over hundreds of acres would be altered to predominantly fir in pole-sawtimber trees, but seedling composition would not immediately change. Since the remaining seedbearing spruce would not immediately produce seed, and would be so few in comparison with the total number of fir, the percentage of spruce seedlings would probably decline in the unlogged stand.

Figure 4.—Dense herbaceous vegetation inhibits seedling establishment—Unlogged site at Deep Lake.

If logging begins immediately after the outbreak, light cutting to remove only the dead spruce would not essentially alter the pole-sawtimber spruce-fir ratio, and would slightly increase the percentage of spruce seedlings. However, since only a few seed-bearing spruce are alive in the immediate area and the size of the infestation would prevent seeding from adjacent uninfested stands, available germination sites would generally be taken by fir seedlings or herbaceous vegetation.

If cutting is heavy (both dead spruce and merchantable fir removed), then the percentages of pole-sawtimber spruce and fir would change because the fir component is reduced. The spruce-fir seedling percentages would change to that species able to provide seed. If logging is so intense that all dead spruce is salvaged and most of the live trees are cut or destroyed during logging, then the site would be occupied by herbaceous vegetation.

2. A spruce-fir stand sustaining an intense attack over a limited area (for example, only a few acres) would be altered to fir in pole-sawtimber trees, but would not immediately change its seedling composition. Fir seedlings would be favored in subsequent years if the soil were not disturbed. Seedbearing fir in the infested area as well as fir and spruce in the adjacent uninfested area would provide seed, but the fir would be more successful in the undisturbed site. Limited logging would create more favorable sites for spruce, but changes in the seedling composition would be related to seed production of each species coincident with logging. Logging equivalent to clearcutting could change the infested area to herbaceous vegetation.

3. A spruce-fir stand sustaining a light infestation over either an extensive or limited area would reduce the percentage of pole-sawtimber spruce, but would not immediately alter the seedling composition. Both spruce and fir would contribute seed, but the undisturbed stand would favor fir. If logging were initiated, anything short of clearcutting would increase the spruce component but would again depend on the production of seed coincident with the creation of favorable germination sites by logging. Otherwise, the sites would be occupied by herbaceous vegetation.

Big-Game, Recreational, Fire, and Decay Implications

Death of the larger trees may have long-term effects on big-game populations. Initially, the killing of the stands improves the summer forage for deer and elk (Yeager and Riordan 1953). This improvement probably continues until the site is fully occupied and forage does not decrease in quantity until new trees begin competing with it. Judging by the rate of seedling and BA growth, forage would not decline substantially for several decades. However, the increasing numbers of fallen dead trees may inhibit the movements of elk and deer, both foraging and between their summer and winter ranges.

Beetle-killed stands also pose a problem for recreationists and land-managing agencies. The recreationist must maintain constant awareness in these stands, while the agency has increased trail maintenance and campground costs.

Beetle-killed spruce become hazards for recreationists because the trees decay and fall, or are windthrown before decaying. In spruce-fir, Hinds et al. (1965) found 12 percent of the volume of each tree decayed and 25 percent of the trees windthrown within 20 years after the outbreak. On our Ripple Creek plots, 10 percent of the trees were windthrown the first 10 years after the outbreak, another 12 percent the second decade, and an additional 26 percent the third decade. Thus, about 1.5 percent of the dead spruce are windthrown each year, although the rate of windfall is increasing. While standing trees do not decay rapidly, fallen trees will decay in 5 years if they are touching the ground. Decomposition is slower for the parts of the logs that do not touch the ground.

Windthrow losses are greater in dead spruce-lodgepole pine stands. In the Rio Blanco Ranch area, windthrow averaged 3.0 and 2.3 percent per year for spruce and lodgepole pine, respectively, for the past 25 years. Why 63 percent of the dead spruce-lodgepole have fallen in the Rio Blanco area while only 46 percent of the spruce have fallen near Ripple Creek Pass is not known.

Windthrow in pure spruce on the Boulder Top amounted to 16 percent about 30 years after the infestation (Mielke 1950). In 1971, 63 percent of the spruce had fallen in the unlogged sample area, thus indicating an average rate of 1.3 percent per year.

Since beetle-killed spruce in a large infestation cannot normally be immediately salvaged, how long can salvage operations continue? Decay and windthrow data indicate salvage could continue up to 20 years after the infestation. Salvage can continue after that period if special uses (mine props) for the dead spruce can be found. However, such operations are marginal and the longer they continue, the less profitable they become.

Beetle-killed trees originating from outbreaks may become a high fire hazard. In 1951, then Forest Service Chief Watts suggested that the spruce beetle outbreak was creating a very serious fire hazard in Colorado, and money for control should be expended to reduce this hazard (U.S. Senate 1952). During the 25 to 30 years since the outbreak, no major fires developed. Furthermore, widespread fire seems to be a rare event in the spruce-fir type. Mielke (1950) stated that no large fires have burned in the spruce-fir in Colorado since 1900, and one major fire in 1879 in northern Colorado (Routt National Forest) was started by Indians. Miller (1970) noted that evidence of widespread fires between 1750 and 1830 is lacking on the White River Plateau. Although the beetle-killed snags are potential lightning rods and the massive number of dead trees has created a large fuel buildup, the fire hazard seems overexaggerated. Lightning in summer thunderstorms could start fires in these snags, but the accompanying rainfall apparently dampens the surrounding vegetation enough to prevent development of a widespread fire. Thus the importance of the fire hazard in the spruce-fir is less than in other timber types.

Characteristics of Potential Outbreak Stands

Analysis of these four infestations suggests some characteristics of potential outbreak stands: (1) spruce-fir stands of predominantly spruce in the canopy—the higher the percentage of spruce the greater the potential; (2) BA of 150 to 200+ ft per acre, with the BA concentrated in older, large-diameter spruce; (3) single- or two-storied stands; and (4) an average rate of diameter growth of 0.04 inch or less per 10 years.

Most of these characteristics were present in the infestations. They indicate those stands with high susceptibility that can develop into outbreak areas if the beetle population builds up. Because strong winds, lack of windfirmness, and endemic beetle populations are typical throughout the spruce type, the probability is high that a substantial outbreak could develop whenever these conditions are found. Because these characteristics are generally absent in some stands does not mean they could not be attacked by beetles. It does mean, however, that chances for development of an outbreak are considerably less.

Succession in Spruce-Fir Stands

The characteristics of potential outbreak stands and the changes in species composition caused by beetle infestations provide a basis for speculating on ecological succession in the spruce-fir type. Daubenmire (1943) classified spruce-fir as the climatic climax. Alexander[3] predicts that spruce is the climax species in the central Rockies, and will eventually replace the fir if the stand is not disturbed. Miller (1970) correlated age structure in spruce-fir stands in the central Rocky Mountains with spruce beetle outbreaks, but did not speculate on stand succession. We agree with Miller, but further suggest that the combined forces of spruce beetles, and *Dryocoetes confusus* Swaine and associated fungi alter the status of the spruce and fir components over the years, first toward fir, then toward spruce, and then back to fir as each species matures and spruce beetles periodically reach outbreak status.

The development of a spruce-fir forest over several centuries might be as follows: Assume a stand like one of those on the White River National Forest after the beetle outbreak in the 1940's; 80 percent fir-20 percent spruce in trees larger than 3 inches d.b.h., and the same or a higher percentage of fir in the seedling class. Both species grow rapidly. Fir continues to predominate and slightly increases its components in the overstory (fig. 5). As the overstory firs reach a diameter of 16 to 18 inches d.b.h. or 125 to 175 years they begin to die and fall out of the overstory. Why fir dies is not completely understood, but Swaine (1933) cites *D. confusus* Swaine as a mortality agent in British Columbia, and Molnar (1965) identified a *D. confusus*-fungus complex as killing 6- to 15-inch fir. The total BA curve reflects these decreases due to the loss of fir (fig. 5). Younger spruce and fir use these unoccupied sites and increase in size, but the spruce component in the overstory increases proportionately more than the fir.

Meanwhile, more seedlings are becoming established so that the spruce component is

[3]*Personal communication with Robert R. Alexander, Principal Silviculturist, Rocky Mt. For. and Range Exp. Stn., USDA Forest Service, Fort Collins, Colo.*

increasing slightly because of two factors. First, even though fir seedlings vastly outnumber spruce seedlings, the original removal of the canopy by the beetles favors the less tolerant spruce more than it does the highly tolerant fir. This allows spruce seedlings to compete more vigorously with fir, whereas prior to the outbreak fir was in the more advantageous position. Secondly, more leaders of fir seedlings are heavily damaged by animals or other factors than spruce, so spruce gains valuable height on fir. Eventually, since spruce lives longer and attains greater size (LeBarron and Jemison 1953), it becomes dominant. At this point, the fir occupies a lesser percentage of the canopy.

Total BA begins to increase rapidly and proceeds toward the potential of the site as the maturing spruce grow. At periodic intervals, spruce beetle outbreaks reduce the total BA and the spruce component, as Miller (1970) suggests, but the initial outbreaks kill less than 50 percent of the spruce (probably 10 to 20 percent as Frye and Flake (1972), or 25 to 40 percent as Sudworth (1898b) report) before the beetle population subsides because of natural factors.

Such outbreaks are probably examples of the "pocket biology" of the spruce beetle—a situation where the beetles reach outbreak status in a generally immature stand with pockets of larger diameter trees.[4] The spruce component decreases and fir increases, but the spruce still occupies more than 50 percent of the live BA. As the stand recovers after each outbreak, the stand tends more toward a single story. The stand continues to grow and approaches maximum BA. It is now highly susceptible to spruce beetle outbreaks. Eventually, given the moisture and wind conditions characteristic in the central Rockies, blowdown occurs. Spruce beetles develop to outbreak proportions in the downed material, and attack the surrounding standing spruce, killing it so that the stand becomes fir and the transition from predominantly fir to spruce to fir is complete.

The trend of the total BA curve after the stand reaches the site potential and sustains an outbreak (fig. 5, point A) is open to further investi-

[4]*Personal communication with R. H. Frye, and H. W. Flake, Jr., Entomologists, USDA Forest Service.*

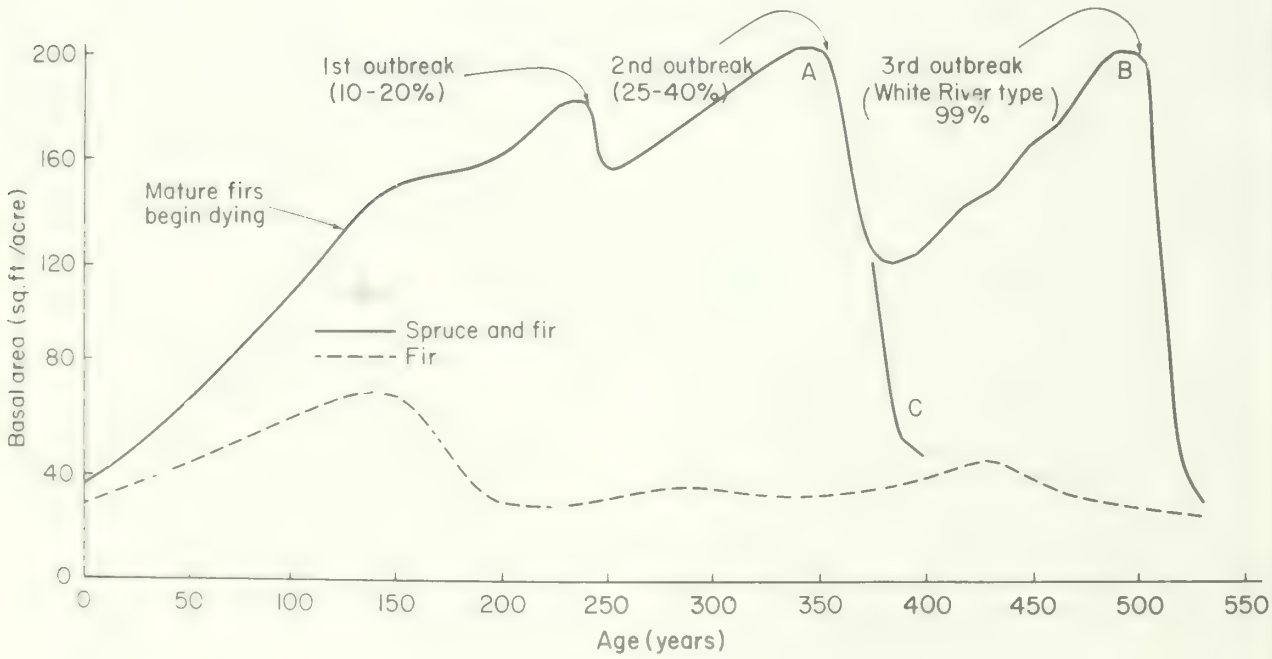

Figure 5.—Hypothetical succession curve of spruce-fir.

gation. It may proceed in a wavelike trend resulting from intensive outbreaks (point B), continue downward from an expanding initial infestation (point C), or remain relatively static with minor fluctuations due to endemic infestations (not shown). Historical data and knowledge of spruce-fir stands suggest the wavelike trend is probably the most likely.

Conclusions

In answering the original question "Wouldn't it have been better to let the outbreak run its course," a qualified "no" is appropriate. Assuming the Lone Cone outbreak threatened the spruce-fir type of the San Juan country and the White River outbreak threatened the same type in Colorado, northern New Mexico, and southern Wyoming (Brannan in U.S. Senate 1952) then control was expedient, not because of the potential fire or flood hazards (both overexaggerated) but because of the total resource value. We do not have enough specific information to assign positive or negative values to the recreation, wildlife, and other considerations. However, within some specific areas of the Lone Cone and White River infestations, the control or salvage methods used were contrary to the objective of perpetuating the timber resource. Clearcutting and mechanized skidding operations badly disrupted the forested area, and may have delayed natural regeneration for 50 to 100 years. Restricted salvage, on the other hand, would have allowed a limited recovery of the timber resource without undue damage to the future forest.

Our qualified answer may not be appropriate, depending on a person's point of view about whether natural forces should be allowed to operate uninhibited in the forest. However, most should agree that factors such as values saved or lost, desires of the public, objectives of the land manager, and finances create a complex situation for which there is no answer agreeable to all.

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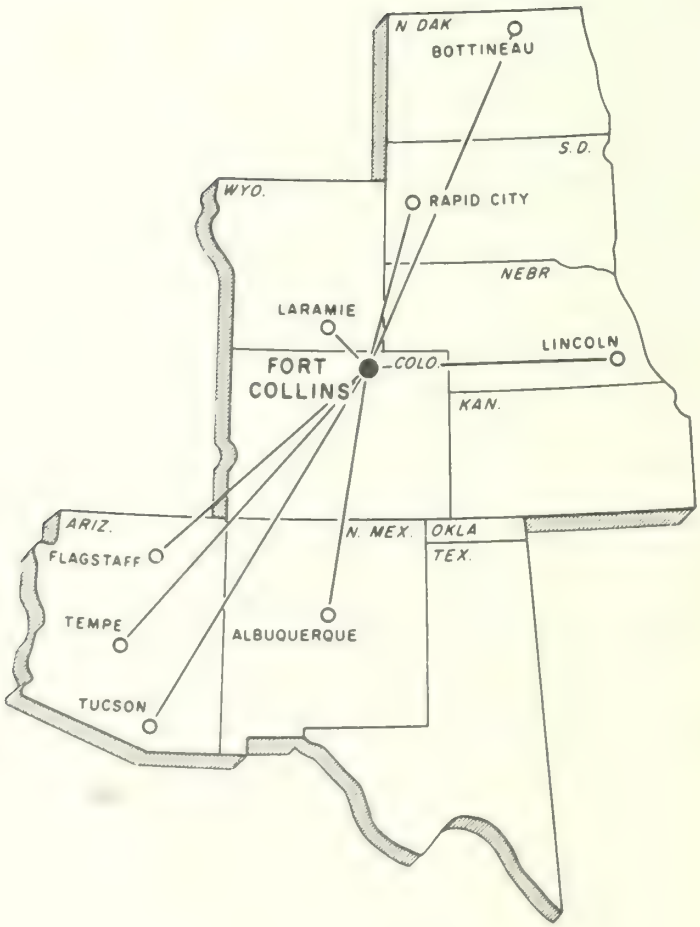
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December 1974

Multipurpose Silviculture in Ponderosa Pine Stands of the Montane Zone of Central Colorado

Clifford A. Myers

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USDA Forest Service
Research Paper RM-132
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado 80521

Abstract

Presents silvicultural prescriptions for ponderosa pine in an area where several uses and products of the forest are important but scenic and recreation values predominate. Although far from virgin condition, the pine stands now bear little resemblance to a managed, regulated forest. Present diversity within and between vegetative types can and should be maintained.

Keywords: Forest cutting systems, *Pinus ponderosa*, silviculture, stand condition, thinning (trees), timber management.

Acknowledgment

Efforts of past and present personnel of the Pike-San Isabel National Forest in accomplishing the treatments described herein are gratefully acknowledged.

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Multipurpose Silviculture in Ponderosa Pine Stands of the Montane Zone of Central Colorado

by

Clifford A. Myers, Chief Mensurationist

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University.*

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Multipurpose Silviculture in Ponderosa Pine Stands of the Montane Zone of Central Colorado

Clifford A. Myers

Guides are presented here for silvicultural practices in ponderosa pine[2] stands of the Montane Zone of central Colorado. This Zone is the first timbered belt above the Plains on the east side of the Colorado Rockies, at elevations from about 6,500 to 9,400 ft (Miller and Choate 1964). Altitudinal limits vary locally with latitude, aspect, and soil depth. The Zone includes the eastern parts of the Arapaho-Roosevelt and Pike-San Isabel National Forests plus other lands along the same north-south axis.

Another way of locating the Zone geographically emphasizes its peculiar management problems and the need for multipurpose silviculture. It is the closest forest land to the largest cities of Colorado and to the homes of visitors from the East. The Zone, therefore, is the most heavily used timbered area of Colorado. Use is continuous, since the entire Zone is readily accessible yearlong for residence, recreation, and other purposes.

Soil and weather factors of the Montane Zone of central Colorado determine possible uses of the area, relative resistance of the land to abuse, and which silvicultural methods are practical. Annual precipitation is very low for tree growth, averaging from 15 to 20 inches. Seasonal distribution of precipitation, however, compensates to some extent for the small total amount. About two-thirds of the annual precipitation falls during spring and summer when it is most useful for regeneration and growth.

Geologically, the Montane Zone includes parts of the Front Range, Sangre de Cristo Mountains, Spanish Peaks, and the Wet Mountains. Soil parent materials of the Zone, therefore, include a full range of igneous, sedimentary, and metamorphic rocks and the alluvium derived from them (Marcus 1973). Residual soils of low fertility from several large granitic plutons cover much of the Zone. They are important factors in management decisions involving any resources and uses of the land because of potentially serious erosion following major disturbance of the vegetative cover.

For brevity, the term "Montane Zone" elsewhere in this publication refers only to that part described above, along the east side of the Rocky Mountains in central Colorado.

[2]*Scientific names of species mentioned are listed on page 15.*

The guides are based on (1) data from the Zone and from the Black Hills of South Dakota and Wyoming, and (2) experience gained during six applications of the marking prescriptions to a total of about 2,000 acres of the Manitou Experimental Forest, Colorado. In addition, operational utility of the prescriptions has been tested on the Pike-San Isabel Forest.

The Manitou Experimental Forest provides, on a small area, most of the land use situations faced by managers throughout the Montane Zone. The 2,000 acres referred to above lie along a main State highway and are adjacent to or visible from two campgrounds, a large picnic and fishing area, a rural housing development, and a church camp. The Experimental Forest provides food and cover for about 150 species of birds, other wild animals, and domestic livestock. Interest in animals by visitors ranges from that of birders expanding their life lists to the desire of children from urban areas to see a "real cow." Wood produced during treatment of the forested areas for various management objectives helps support a small wood products industry.

Four terms are used in the following sections to distinguish timbered areas of various sizes. They are defined as follows:

Treatment Area—A large area of up to several hundred acres that is treated during a single period of cutting. Equivalent to a small "sale area" in timber sales contracts.

Stand—A subdivision of a treatment area that is several acres in size. Minimum area of a stand will vary with such factors as class of ownership and the objectives of management. In the Montane Zone, stands will probably be 5 acres or larger. The term is used as in management texts and is applicable to an area of even-aged or many-aged trees that can be regenerated by a single reproduction method. In addition, a stand is large enough to be mapped and to serve as a practical unit for growth estimation.

Patch—An area of trees of relatively uniform density, tree quality, and age structure that is too small to be treated as a stand. It cannot receive individual consideration in mapping, inventory, and growth prediction. Small patches occur so frequently, they merit separate consideration, as in the next definition.

Group—A small, even-aged patch of trees such as results from a single application of group selection. Groups will usually range in area from ½ to 1 acre.

Although mentioned only briefly, vegetative types other than ponderosa pine are important resources of the Zone. They create a desirable diversity in scenery and in uses made of the land. Other vegetative types include grasslands, Douglas-fir groups and stands, aspen groves, streamside willow thickets, and blue spruce. Douglas-firs occur as scattered trees in pine stands as well as in pure patches and stands on north-facing slopes and along streams. Retaining young, vigorous Douglas-firs in pine stands will usually be beneficial.

Stand Characteristics

Biological characteristics of ponderosa pine stands that influence selection of silvicultural practices are highly variable in the Montane Zone (fig. 1). Most obvious are variations in stand density, age class distribution, tree vigor, presence of diseases and insects, and size of the patches of uniform density and age structure that make up the forest mosaic. Present conditions are the result of past logging, insect and disease attacks, fires, and irregularity in the coincidence of weather and other factors favorable to regeneration. Although the stands are far removed from virgin condition, they bear little resemblance to a fully managed, regulated forest. A practical attempt to select treatments requires that the multitude of minor variations be logically collected in a few broad classes of characteristics.

Figure 1.—Ponderosa pines of the Montane Zone form a complex mosaic of variations in tree size and stand density.

Frequently, events of the past have created patches and stands that, by accident, appear to have resulted from application of standard reproduction methods. It is convenient to regard these resemblances as intentional, and to plan and carry out treatments in terms of these methods. By ignoring structural variations that involve only scattered small patches, three general situations can be recognized. These situations, to be considered when selecting treatments, are:

Situation 1.—Many areas large enough to be managed as uneven-aged stands have an irregular mosaic of small, even-aged patches of trees. Such stands resemble the results attainable from group selection cuttings at irregular time intervals. Each even-aged group covers an area equal to what could be fully occupied by a few mature trees, prehaps ½ to 1 acre.

Situation 2.—Other stands are made up of patches that are individually smaller than the 5 or more acres of a manageable stand but larger than ½ to 1 acre. Such a patch is, therefore, too large to resemble a group resulting from usual applications of group selection.

Situation 3.—Some stand-size areas appear to be even-aged or two-storied, as though regenerated by uniform shelterwood, seed tree, or clearcutting methods. Many stands properly classed as being in this situation appear highly irregular before treatment. Cuttings necessary to improve the health, vigor, and appearance of such stands, however, will produce greater uniformity in density and age structure.

Recognition of any of the three situations listed here must be based on the real management problem and not on correctable accidents of past stand history.

Factors in addition to stand condition call for flexibility in the silvicultural prescriptions for ponderosa pine. Some factors are of major importance for most classes of ownership and most management objectives applicable to the Zone. The principal forest values derived from the Zone relate to beauty of the landscape and to various forms of outdoor recreation. Silviculture, in most areas, is not a tool to obtain maximum production of wood products. Instead, it is a means of improving the quality and diversity of the landscape and of providing as high a potential for a variety of uses as is compatible with carrying capacity of the land. Silviculture thus

becomes a landscaping tool and a means of reducing the damage from mountain pine beetles, dwarf mistletoe, and other agents that can lower the attractiveness and usefulness of the Zone. Wood products produced while these improvements are being made help keep alive an industry that is important to Colorado.

Since the values received from the Zone relate largely to scenery and recreation, the question may be raised: "Why do any cutting at all?" Nontreatment is not a suitable alternative for interior ponderosa pine for several reasons. These include:

1. Patches and stands that are old and diseased must be replaced to create the scenic and recreation areas of the future. Untouched, they can only become more unattractive with the passage of time (fig. 2). It is possible to grow ponderosa pines to advanced ages, although they do not reach the ages in the central and southern Rocky Mountains that they do to the north and west (Sudworth 1917). The difficulty is that too many of our larger trees have already reached a diseased and lightning-scarred old age. Regenerating patches or stands while they can still produce seeds avoids the high costs and risks of planting. Reproduction from seed can accumulate over several years so there is no dependence on planting during what may be a year of adverse weather conditions.

2. Dense patches and stands of young ponderosa pines on areas of low site quality will stagnate. Tree diameters stay small for many years and the problem is not relieved by natural thinning (Myers and Van Deusen 1960). Evidence of slow growth in unthinned stands includes such examples as trees more than 60 years old with average diameters of 2.5 inches. Dense patches and stands are unattractive; impede use by people, deer, and cattle; block the view of more scenic areas; and create a biological desert on the forest floor (fig. 3). Ponderosa pines in the Montane Zone of central Colorado grow on areas of low site quality and are, thereby, subject to stagnation. They must be thinned, if of high density, to avoid the disadvantages of stagnation.

3. Any patch or stand that is not already stagnated will become more dense with the passage of time. Crowding reduces tree growth and vigor and increases susceptibility to damage. For example, high stand density can lead to devastating losses from mountain pine beetles.[3] A survey of past outbreaks in the Montane Zone indicated that epidemic losses can occur even in

[3]*Sartwell, Charles, and Robert E. Stevens. Mountain pine beetle in ponderosa pine: Prospects for silvicultural control in second-growth stands. (Manuscript submitted for publication.)*

Figure 2.—Heavy infestations of dwarf mistletoe greatly reduce scenic beauty and timber yields.

Figure 3.—Dense patches of ponderosa pine contribute little to the appearance and productivity of the Montane Zone.

years of ample rainfall (Beal 1943). Also, increased density will interfere with or prevent the development of a community of understory shrubs and herbaceous plants. This reduces the scenic value of the area and the food supply of wild and domestic animals.

Types of Treatments

Variability of the ponderosa pine type and of its uses usually requires application of several cutting methods to a single treatment area.The alternative is to use drastic methods to move the stands toward some predetermined structure. The Manitou Experimental Forest treatments are examples of how variable a single marking job can be. The cutting methods used at Manitou, described in standard nomenclature, were:

1. Thinning—Reduction of the density of even-aged groups and stands. Thinnings were applied where densities before treatment were high enough to greatly reduce the growth of the trees and the herbaceous ground cover. Young trees left after final removal of a shelterwood were also thinned, if necessary. Trees varying more than 20 years in actual age sometimes appeared to have the diameter distributions of even-aged stands because of unequal diameter growth caused by past irregularity in density. Such patches and stands were treated as though they were truly even-aged.

Nature of the thinnings varied with size of the trees and stand conditions created by past damage or cutting. Most precommercial thinnings and commercial cuts in trees of small average diameter were heavy low thinnings (thinnings from below). Emphasis was on removal of the lowest crown classes and enough dominants and codominants to stimulate growth of the residuals. Some dense groups and stands were overtopped by isolated larger trees, poor quality residuals of the previous generation that remained alive after logging or fires. These stands and most of those composed of large trees only were cut by free thinning procedures, as defined by Smith (1962). In free thinning situations, low thinning was accompanied by (a) removal of scattered overstory trees, (b) felling of undesirable dominants, and (c) any necessary release among the dominant and codominant trees of the main stand.

2. Improvement—Removal of badly diseased and dying trees that interfered with or overtopped those selected for future growth. Improvement cutting was done where (a) patches or stands not dense enough to require complete thinning had occasional trees that should be removed, or (b) single poor trees remained over even-aged patches. Past fires and logging in the Montane Zone have left most present stands badly in need of improvement cutting. Application of all needed improvement at once could materially degrade scenic and other values. It may be desirable to make two or more improvement cuts in stands where many trees should be removed, and where the effects of further delay can be tolerated.

3. Clearcutting with or without planting—Removal of patches or stands of trees so badly infested with dwarf mistletoe that they could not produce seed and were dying rapidly.

4. Seed cut of uniform shelterwood—Reduction of the density of mature trees to encourage the establishment of natural regeneration over an area large enough to be treated as a stand.

5. Final cut of uniform shelterwood—Removal of overstory trees to release an adequately stocked understory. Prior cutting and natural disturbances affecting entire stands occurred so long ago that cuttings resembling removals prior to final cuts were not needed.

6. Group selection—Removal of a group of mature trees with intent to obtain natural regeneration from seeds produced adjacent to the area occupied by the group. When following specifications for group selection, it is imperative that markers do not create some of the poor stand conditions they are trying to prevent. Old and declining trees must not be retained just because they are relatively small and thus appear younger than they are. Chances for this error are especially great with ponderosa pine, where a tendency to stagnate often results in poor correlation between tree age and diameter. If the marker is to leave the younger, more vigorous trees, he must be sure he is doing so. If all the trees in a stand are old and declining, regeneration under a shelterwood may be appropriate.

Selecting Treatments

Prescriptions for treatment areas at Manitou (200 to 600 acres each) called for concurrent application of all six methods. Improvement cutting and thinning were accomplished in even-aged groups and stands, where necessary. Each stand to be regenerated in whole or part was cut according to a single reproduction method, selected to meet the needs of the stand and the management objectives for the forest.

Occasional interior patches of quite dissimilar conditions, however, were treated on the basis of their status and not on that of the stand as a whole. Otherwise, good trees would have been sacrificed for the sake of uniformity. For example, patches of young, vigorous trees in stands marked for shelterwood seed cuts were thinned, if necessary. Additional considerations in applying the cutting methods are described in the section "**Applying Treatments.**"

When evaluating stand density as an indicator of the need for thinning or of space requirements for regeneration, the real indicator of competition is not visible. Degree of crown closure is not a useful guide under the dry conditions of the Montane Zone. Instead, the extent of site occupancy by tree roots determines tree vigor and ease of regeneration. Ponderosa pine stands are adequately stocked when the crowns are still well separated. This is why some managers define proper stocking as 50 to 60 percent of the "room to grow and none to waste" values of normal yield tables. With the principal factors determining degree of site occupancy underground, the system of designating stocking goals described in the next section, **Reserve Stands**, provides a useful guide for marking crews. Root competition appears to be a less serious factor in Colorado than in Arizona, and more important than in the Black Hills.

Most areas to be regenerated were cut according to prescriptions for group selection or uniform shelterwood. In applying shelterwood cuts to even-aged and two-storied stands (**situation 3** of the section titled **Stand Characteristics**), the regeneration period of each stand was begun or terminated by the cutting. Selection of a seed or final cut depended on the presence or absence of younger trees. A pine understory, if adequate in amount and quality, was regarded as the logical consequence of prior shelterwood cuts. Appropriate parts of uneven-aged stands were regenerated by group selection. Where the even-aged units were about ½ to 1 acre in area, the cut covered the entire area of each selected group (**situation 1**). With patches larger than ½ to 1 acre, the poorest parts of scattered patches of old trees were cut as single groups (**situation 2**). These parts were selected on the basis of advanced age, low tree vigor, high incidence of disease, and a very low density. Occasionally, however, large patches of rapidly declining trees were marked for a shelterwood seed cut, to avoid the undesirable effects of delayed treatment. Groups (**situation 1**) or parts of patches (**situation 2**) not cut for regeneration received an improvement cut, a thinning, or were left alone. Clearcutting was classed as a drastic treatment to be avoided except where there was no alternative for solving severe disease problems.

Reproduction appeared to be adequate in amount by the third year after each cutting and, after 6 years, remains abundant on regeneration areas of the first treatment (fig. 4). Length of the period of germination and establishment can vary at Manitou and elsewhere with weather conditions and with position of the treatment year in a seed production cycle. Areas under a shelterwood, in cleared groups of ½ to 1 acre, and in the narrower parts of clearcut areas all regenerated satisfactorily. Good range management practices and moderate grazing use are expected to prevent significant future losses of pine seedlings to livestock (Heerwagen 1954).

Figure 4.—Group selection and shelterwood provide the openings needed for ponderosa pine seedlings to become established.

Presence of a suitable seed source is essential to natural regeneration. For best results, trees depended upon for seed should be 60 to 160 years old. Older and younger trees, however, do produce viable seeds. Seed trees must not have a dwarf mistletoe rating (fig. 5) greater than 3.0.[4] With group selection and clearcutting with natural regeneration, none of the cleared area should be more than about 150 ft from an acceptable seed tree.

[4]*Personal communication with Frank G. Hawksworth, Chief Plant Pathologist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.*

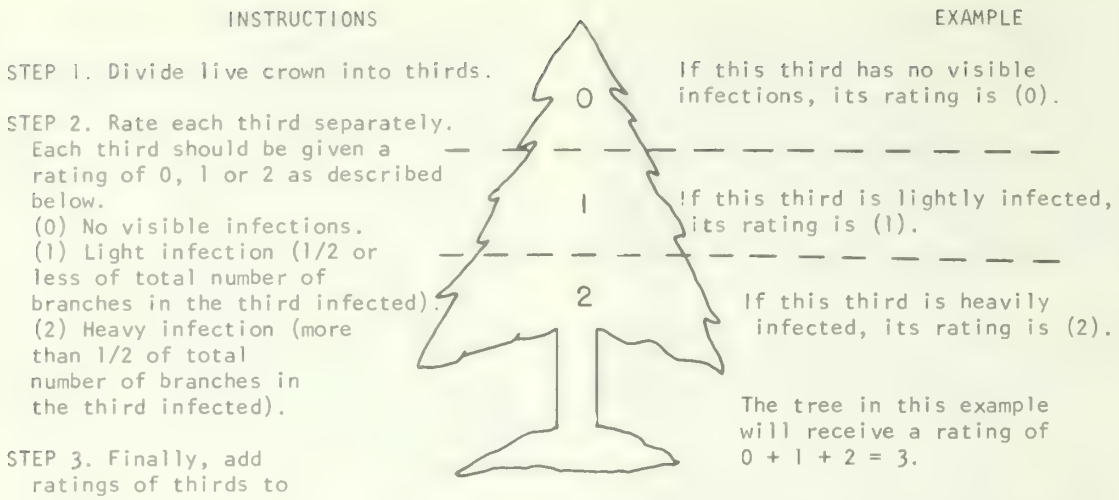
INSTRUCTIONS
STEP 1. Divide live crown into thirds.
STEP 2. Rate each third separately. Each third should be given a rating of 0, 1 or 2 as described below.
(0) No visible infections.
(1) Light infection (1/2 or less of total number of branches in the third infected).
(2) Heavy infection (more than 1/2 of total number of branches in the third infected).
STEP 3. Finally, add ratings of thirds to obtain rating for total tree.
EXAMPLE
If this third has no visible infections, its rating is (0).
0
1
If this third is lightly infected, its rating is (1).
2
If this third is heavily infected, its rating is (2).
The tree in this example will receive a rating of 0 + 1 + 2 = 3.

Figure 5.—Instructions for and example of the use of the 6-class mistletoe rating system (Hawksworth 1961).

Regeneration problems of the Montane Zone can be described further by explaining why certain standard reproduction methods were not used at Manitou. Single-tree selection was not used because: (1) no areas would be freed of root competition to provide space for reproduction, (2) nothing could be done to reduce dwarf mistletoe infestations, and (3) the method was rarely in accord with the age or size structure of any stand. Shelterwood was chosen over the seed-tree method to increase the chances of getting adequate natural regeneration within a few years of cutting. Regeneration can be successful when a good seed supply coincides with weather conditions favorable for germination and seedling establishment. By leaving more seed-producing trees, there will be more years when the seed supply per acre is adequate and, thus, more opportunities for coincidence with favorable weather conditions. Also, the volume left in a shelterwood is enough to justify its eventual removal to favor the new stand.

An appropriate cutting method for each stand condition on a treatment area should be selected during marking. As the marker moves from one condition to another, he should ask himself a series of questions, such as:

—Does this unit cover a large enough area to be treated as a single stand?
—If so, which of the three general types of structure does it most resemble?
—If it is not a stand, should I treat the unit separately from the rest of the stand?
—Can I leave the unit alone until the next entry into the entire treatment area?
—If it should be treated, are the trees old enough and of such condition that I should consider a regeneration cut?
—If so, is there any advance reproduction?
—If a regeneration cut is in order, what do I want this unit to look like in the future and what regeneration method will produce what I want?
—If regeneration is not appropriate now, do I want to thin or is an improvement cut to remove a few undesirable trees called for?
—Now that I have tentatively selected a type of marking for this unit, must I modify it because of effects on the scenery, on wildlife habitat and food supply, or on the soil?

A marker need not concern himself with the effect of his choice of method on logging costs. Under Montane Zone conditions, logging costs are not expected to depend to any important degree on the type of regeneration method selected. This assumption has been tested in detail and accepted as correct elsewhere in the ponderosa pine type (McDonald et al. 1969).

In summary, each patch or stand of a treatment area should receive the treatment most appropriate to its condition, usually without regard to the cutting method used on adjacent patches or stands. Posttreatment status of adjacent areas must be considered if they are to serve as seed sources. It is unnecessary to attempt creation of larger, more uniform stands, although this will often happen because existing stand conditions do not permit many alternatives. Maintenance of irregularity is acceptable, even desirable, so long as it will not perpetuate intolerable conditions of disease or high stand density.

One restriction may limit freedom in use of the six cutting methods listed above: Individual clearcuts for disease control along regularly traveled forest roads should be no larger than the ½- to 1-acre units of group selection. Other than that, roadside strips need no special treatment. Cuttings continue to the roads without change in density of the reserve stand or other specifications.

Once a cutting method is selected for a patch or stand, it is marked to accomplish management objectives and to leave the best trees at the desired density. With one exception, basal area reserves for intermediate cuts at Manitou equaled growing stock level 80, as defined in the next section, **Reserve Stands.** Level 80 was selected as the best compromise to achieve all objectives of the treatments. Growing stock level 100 would have been chosen if major emphasis had been placed on timber production.

Posttreatment observations and data support selection of level 80, as follows:

1. Treated stands are open enough to provide pleasing views into the stands and to allow the growth of wildflowers, yet are not so open as to lessen the scenic impact of the forest or to lose the forest environment.

2. Total wood production in ft^3 of stands repeatedly thinned to level 80 was estimated to be about 85 percent of the maximum possible for average site quality of the treated areas.

3. With any reasonable cutting cycle, basal areas of trees large enough to support brood populations of mountain pine beetles will not again reach the potential danger level of 150 ft^2 per acre.[5]

4. When basal area of large trees is 80 ft^2 per acre, production of forbs and grasses at Manitou is 15 percent of that from areas without a tree cover. Herbaceous production is not materially different from that of open areas, however, after small-diameter trees have been thinned to lower basal areas appropriate to their size. These relationships, with the great reduction in density that usually results from application of the prescriptions described here, indicate suitable conditions for profitable livestock operations.[6]

5. Allowable stocking of livestock on the treatment areas at Manitou increased an average of 10 percent annually in the first 6 years after the beginning of cutting.[6]

6. Forage available for wildlife has not been measured, but appears to have increased at a rate similar to that of forage used by livestock.

[5]*See footnote 3.*

[6]*Personal communication with P.O. Currie, Principal Range Scientist, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.*

The one exception to level 80 as a stocking standard was the thinning of dense patches of small-diameter trees to level 160, or twice usual basal areas. Trees in dense groups or stands are tall in relation to their diameters because of the unequal effects of density on height and diameter growth. Slender trees are very subject to snow bend and snow break for about 6 years after thinning, a period of adjustment of bole form in response to increased exposure (Myers 1963). Probability of a wet spring snow before form adjustment is completed is high in the Montane Zone. Higher posttreatment density was expected to provide enough well-formed trees to permit leaving a group of adequate density after a second thinning in about 10 years.

Potential problem areas for snow damage may be identified in two ways. Patches or stands with a pretreatment density of four or more times the basal area of level 80 (table 1) are subject to heavy snow damage after thinning. Likewise, trees may bend or break after thinning if their height-diameter ratios equal or exceed 90. This ratio is obtained by dividing total height by d.b.h. outside bark, both in the same units of measure.

Reserve Stands

Numbers of trees standing after partial cutting is a major factor in attaining the objectives of intermediate and regeneration cuts. A numerical system for designating stocking goals is desirable so both the manager and the field crews have a common understanding of what is needed. The system must be flexible because management objectives and relative emphasis on forest values can vary from area to area. The system described below has been used with success in the Montane Zone, both in planning and in actual marking for cutting. It applies to even-aged stands and to the even-aged groups created by group selection.

Stand density after treatment is expressed as a relationship between basal area and average stand diameter after cutting (fig. 6). Results of thinning studies and data from temporary plots in even-aged stands were used to obtain regression equations of desired basal area on average stand diameter for stands of average site quality. "Best" stand density for each average diameter sampled was based on a forecast of production in ft^3 and probable length of saw-log rotations. Solution of the regression equations produced the line labeled 80 in figure 6 and the basal areas of table 1. A level is named by the basal area desired when average diameter is 10.0 inches (fig. 6). Basal areas increase with diameter until 10.0 inches diameter is reached,

Table 1.--Basal areas after partial cutting in relation to average stand diameter, growing stock level 80

Average stand d.b.h. after cutting (Inches)	Basal area per acre	Average stand d.b.h. after cutting (Inches)	Basal area per acre	Average stand d.b.h. after cutting (Inches)	Basal area per acre	Average stand d.b.h. after cutting (Inches)	Basal area per acre
	ft^2		ft^2		ft^2		ft^2
2.0	12.1	4.0	35.2	6.0	56.6	8.0	72.5
2.1	13.2	4.1	36.4	6.1	57.6	8.1	73.1
2.2	14.4	4.2	37.6	6.2	58.5	8.2	73.7
2.3	15.5	4.3	38.7	6.3	59.4	8.3	74.3
2.4	16.7	4.4	39.9	6.4	60.3	8.4	74.8
2.5	17.9	4.5	41.0	6.5	61.2	8.5	75.3
2.6	19.0	4.6	42.2	6.6	62.1	8.6	75.8
2.7	20.2	4.7	43.4	6.7	62.9	8.7	76.3
2.8	21.3	4.8	44.5	6.8	63.8	8.8	76.7
2.9	22.5	4.9	45.7	6.9	64.6	8.9	77.1
3.0	23.7	5.0	46.8	7.0	65.4	9.0	77.5
3.1	24.8	5.1	47.8	7.1	66.2	9.1	77.9
3.2	26.0	5.2	48.8	7.2	67.0	9.2	78.2
3.3	27.1	5.3	49.8	7.3	67.7	9.3	78.5
3.4	28.3	5.4	50.8	7.4	68.5	9.4	78.8
3.5	29.5	5.5	51.8	7.5	69.2	9.5	79.1
3.6	30.6	5.6	52.8	7.6	69.9	9.6	79.3
3.7	31.8	5.7	53.8	7.7	70.6	9.7	79.5
3.8	32.9	5.8	54.7	7.8	71.2	9.8	79.7
3.9	34.1	5.9	55.7	7.9	71.9	9.9	79.8
						10.0+	80.0

Derived from: $B = 11.58495\ D - 11.09724$ $\quad 2.0 \leq D \leq 5.0$

$B = 7.76226\ D + 0.85289\ D^2 - 0.07952\ D^3 - 3.45624$ $\quad 5.0 < D < 10.0$

- METRIC EQUIVALENT - - - - - - - - - - - - - - - - - - -

Average stand d.b.h. after cutting (cm)	Basal area per ha	Average stand d.b.h. after cutting (cm)	Basal area per ha	Average stand d.b.h. after cutting (cm)	Basal area area ha	Average stand d.b.h. after cutting (cm)	Basal area per ha
	m^2		m^2		m^2		m^2
5.0	2.7	10.0	7.9	15.0	12.8	20.0	16.5
5.5	3.2	10.5	8.4	15.5	13.2	20.5	16.8
6.0	3.7	11.0	9.0	16.0	13.7	21.0	17.0
6.5	4.3	11.5	9.5	16.5	14.1	21.5	17.3
7.0	4.8	12.0	10.0	17.0	14.5	22.0	17.5
7.5	5.3	12.5	10.5	17.5	14.8	22.5	17.7
8.0	5.8	13.0	11.0	18.0	15.2	23.0	17.9
8.5	6.4	13.5	11.5	18.5	15.5	23.5	18.0
9.0	6.9	14.0	11.9	19.0	15.9	24.0	18.2
9.5	7.4	14.5	12.4	19.5	16.2	24.5	18.3
						25.0	18.4
						25.4	18.4

Derived from: $B = 1.04706\ D - 2.54758$ $\quad 5.0 \leq D \leq 12.7$

$B = 0.70156\ D + 0.03035\ D^2 - 0.00111\ D^3 - 0.79344$ $\quad 12.8 \leq D \leq 25.4$

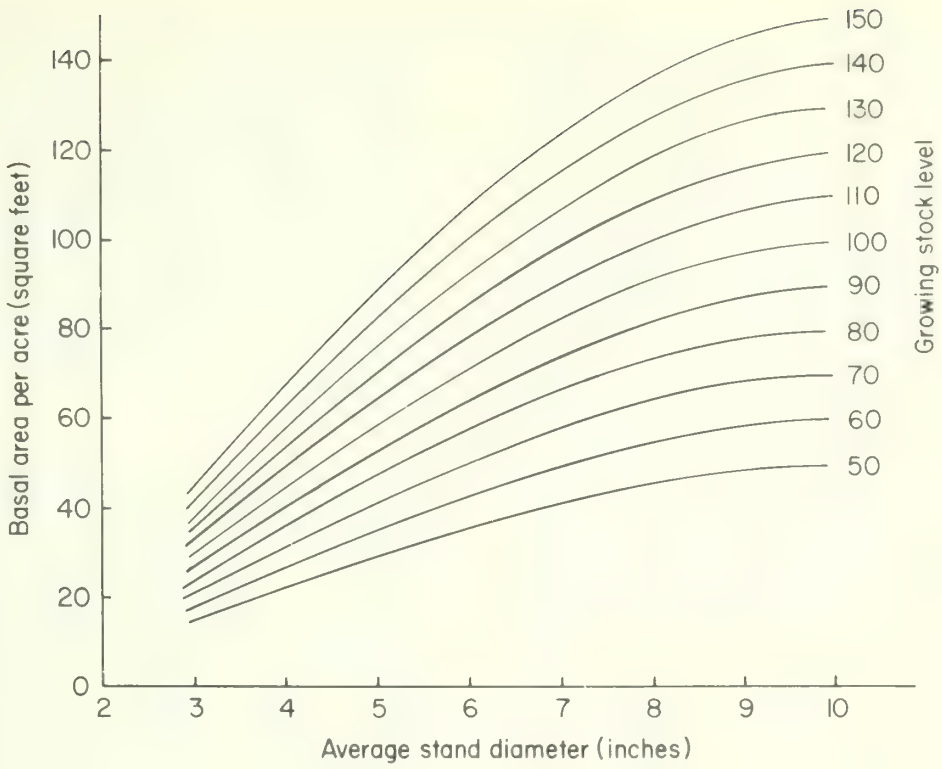

Figure 6.—Basal area after thinning in relation to average stand diameter for standard levels of growing stock.

and remain constant thereafter. The designation "growing stock level 80" indicates that basal area is to be 80.0 ft^2 when average stand diameter after cutting is 10.0 inches or larger.

Desired stand density will vary with the objectives of management; therefore, more than one growing stock level must be defined (fig. 6). The original relationship (level 80) serves as a base from which the basal areas of other levels can be determined. To obtain basal areas for any growing stock level, multiply each value for level 80 in table 1 by the ratio: level/80. Level is the constant basal area desired when average diameter is 10.0 inches or larger. For example, to obtain basal areas for level 100, multiply each value for level 80 in table 1 by 100/80 or 1.25. How basal areas vary with growing stock level in stands of equal average diameter is shown in table 2.

Marking crews may prefer to use average distance between trees rather than basal area as a guide to reserve stocking. In such cases, table 1 or the equivalent for another stocking level is converted to a table of distances. The steps are:

1. Divide basal area per acre by the basal area of a tree of average diameter to obtain the reserve number of trees per acre.

Table 2.--Basal areas after partial cutting in relation to average stand diameter, growing stock levels 40 to 120

Average d.b.h. after cutting (inches)	Basal area in ft^2 when growing stock level is--				
	40	60	80	100	120
1.0	1.8	2.8	3.7	4.6	5.6
2.0	6.0	9.1	12.1	15.1	18.1
3.0	11.8	17.7	23.7	29.6	35.5
4.0	17.6	26.4	35.2	44.1	52.9
5.0	23.4	35.1	46.8	58.5	70.2
6.0	28.3	42.5	56.6	70.8	85.0
7.0	32.7	49.0	65.4	81.7	98.1
8.0	36.3	54.4	72.5	90.6	108.8
9.0	38.8	58.1	77.5	96.9	116.3
10.0+	40.0	60.0	80.0	100.0	120.0

2. Divide 43,560 by the reserve number of trees per acre to obtain the area in ft^2 available to each tree.

3. Obtain the square root of the area available per tree. This is the average distance between trees, assuming a uniform spacing on a grid of squares.

Equivalent distances for the level and diameter combinations of table 2 and for larger diameters are given in table 3.

Table 3.--Growing stock levels for ponderosa pine, expressed as average distance between residual trees

Average d.b.h. after cutting (Inches)	Average distance between residual trees, in ft, when growing stock level is--				
	40	60	80	100	120
1.0	11.4	9.3	8.0	7.2	6.6
2.0	12.5	10.2	8.9	7.9	7.2
3.0	13.4	11.0	9.5	8.5	7.8
4.0	14.7	12.0	10.4	9.3	8.5
5.0	15.9	13.0	11.3	10.1	9.2
6.0	17.4	14.2	12.3	11.0	10.0
7.0	18.9	15.4	13.3	11.9	10.9
8.0	20.5	16.7	14.5	13.0	11.8
9.0	22.3	18.2	15.8	14.1	12.9
10.0	24.4	19.9	17.2	15.4	14.1
11.0	26.8	21.9	19.0	17.0	15.5
12.0	29.2	23.9	20.7	18.5	16.9
13.0	31.7	25.9	22.4	20.0	18.3
14.0	34.1	27.9	24.1	21.6	19.7
15.0	36.6	29.8	25.8	23.1	21.1
16.0	39.0	31.8	27.6	24.7	22.5
17.0	41.4	33.8	29.3	26.2	23.9
18.0	43.9	35.8	31.0	27.7	25.3
19.0	46.3	37.8	32.7	29.3	26.7
20.0	48.7	39.8	34.5	30.8	28.1
- - - - METRIC EQUIVALENT - - - -					
Average d.b.h. after cutting (cm)	Average distance between residual trees, in m, when growing stock level is--				
	9.2	13.8	18.4	23.0	27.5
5.0	3.8	3.1	2.7	2.4	2.2
10.0	4.5	3.6	3.1	2.8	2.6
15.0	5.3	4.3	3.7	3.3	3.0
20.0	6.2	5.0	4.4	3.9	3.6
25.0	7.3	6.0	5.2	4.6	4.3
30.0	8.8	7.2	6.2	5.5	5.1
35.0	10.2	8.4	7.2	6.5	5.9
40.0	11.7	9.6	8.3	7.4	6.8
45.0	13.2	10.7	9.3	8.3	7.6
50.0	14.6	11.9	10.3	9.2	8.4

Stand density specifications described above create an estimation problem when average diameter after cutting will be less than 10.0 inches. The basal area to be left is based on the as yet unknown posttreatment average diameter. It is therefore necessary to estimate diameter after cutting and to determine the basal area goal from table 1 or equivalent. Experience on a number of treatment areas has shown that crews adapt readily to this procedure. Estimates of the effects of cutting on average diameter, such as in table 4, can be helpful in training but do not replace actual changes observed during marking.

Table 4.--Average stand diameters before thinning and after thinning to various levels

Average d.b.h. before thinning (Inches)	Average d.b.h. in inches when percent of trees remaining after thinning is--				
	10	30	50	70	90
3.0	4.7	4.0	3.8	3.5	3.1
4.0	6.0	5.1	4.8	4.5	4.2
5.0	7.2	6.2	5.8	5.5	5.2
6.0	8.4	7.3	6.9	6.6	6.2
7.0	9.6	8.4	7.9	7.6	7.2
8.0	10.8	9.5	9.0	8.6	8.2
9.0	11.9	10.6	10.0	9.6	9.2
10.0	13.0	11.7	11.1	10.7	10.3

Markers must remember that level 80 does not mean a reserve basal area of 80 ft^2 per acre unless average d.b.h. after cutting is 10.0 inches or larger. For smaller average diameters, level 80 means that less, sometimes much less, than 80 ft^2 be left (see table 1). Also, reserve basal area is determined for each individual group or stand treated, not as an average for widely dissimilar conditions.

Marking crews should first walk through each part of the treatment area to determine the type of cutting required and to obtain a mental picture of the group or stand that should be left. Many patches are so small that a marker in the middle of the area can see the patch boundaries. Minor adjustments in the estimate of average diameter after cutting can be made, if necessary, as marking continues. Basal areas of leave trees should be checked periodically with a prism or other angle gage. Inspection of table 1 and of variable-density yield tables (Myers 1971) shows that a high degree of precision is not necessary. Specifications for precommercial thinnings can be presented to the cutters in

the form of previously marked demonstration plots, as described in the next section.

Applying Treatments

Selecting a cutting method for each group or stand, and marking to leave the basal area of the growing stock level chosen are major activities. There are, however, additional tasks to be completed and decisions to be made before the areas are ready for treatment. Some of the more important ones are described below.

Marking for Thinning

Most thinnings can be controlled by marking either the trees to be taken or those to be left. If cutting removes only trees too small for posts or small poles, it may be more efficient to exercise control through demonstration marking. In the latter case, several patches of trees, each of different average tree diameter, should be marked to the residual basal areas desired. This can be done by flagging the reserve trees. Members of the thinning crews visit these sample areas as often as necessary for them to become familiar with the spacings and densities desired for various average diameters. Flagged patches remain unthinned until they are no longer needed as demonstrations.

Slash Disposal

Several methods of slash disposal were tried at Manitou, with varying degrees of success. Piling and burning proved to be so expensive and time consuming that it was soon abandoned. Spot burning was much better if the residual stands were sufficiently open and if the loggers made an effort to keep slash accumulations away from reserved trees. Lopping and scattering required no burning but did require extra effort along roads to get the slash close to the ground and less conspicuous.

Current slash disposal practices involve removing as much slash as possible in the form of small posts and firewood. Commercial cutters remove usable material 2 inches in diameter and larger, and lop and scatter the remaining tops. Areas are also provided for individuals who want only small amounts of firewood for personal use. Removal of posts and fuelwood leaves only small material that does not adversely affect appearance or use of the area (fig. 7).

Wildlife Trees

Before marking trees for removal, those in use as nests or dens by birds and other animals can be tagged with metal signs (4×6 inches at Manitou), reading "Do not cut this tree" (fig. 8).

Figure 7.—Removal of all useful material, including fireplace wood, will usually solve slash disposal problems.

Figure 8.—Trees beneficial to wildlife are valuable elements of Montane Zone stands.

Markers do not paint-spot tagged trees for cutting, and sales contracts warn purchasers that tagged trees are not to be cut during felling of dead and cull trees. Most reserved wildlife trees at Manitou were ponderosa pines used by violet-green swallows, mountain chickadees, Williamson's sapsuckers, and yellow-bellied sapsuckers. Elsewhere in the Montane Zone, the reservation of aspens will also be important, especially for flammulated owls and tree swallows. Ponderosa pines 11 to 30 inches d.b.h. are preferred for food and cover by Abert's squirrels (Patton and Green 1970). Conditions are improved when the rather uniform spacings that usually result from partial cuttings are interrupted by occasional clumps of three or four closely spaced large trees.[7] Maintenance of squirrel populations, therefore, requires that conversion of large areas to seedling and sapling stands be avoided. Development of scattered, young stands of reasonable area creates no special problems. Abert's squirrels in central Arizona were observed to occupy home ranges averaging about 18 acres in summer and fall and 5 acres in winter (Keith 1965).

The low-vigor, large-limbed, or dead trees used by wildlife would be prime choices for removal if special effort were not made to save them. So few trees per acre are involved in this type of habitat maintenance that their preservation will have negligible adverse effect on the appearance of the forest and other values. Regardless of the silvicultural methods applied, tagged trees should remain untouched so long as they are useful to wildlife.

Dwarf Mistletoes

Dwarf mistletoes create a major disease problem in ponderosa pine stands of the Montane Zone that must be considered in planning timber treatments. In general, partial cutting cannot improve the growth and quality of an infested stand if the average DMR (dwarf mistletoe rating) (see fig. 5), is greater than 3.0 (Myers et al. 1972). If the average DMR of an infested stand is less than 3.0, cutting methods are applied as usual except that the cutting of infected trees and pruning of diseased lower branches are emphasized (Lightle and Hawksworth 1973). Pruning that removes more than half the live crown or leaves less than one-third the total tree height in live crown can result in decreased growth or death (Dahms 1954, Gordon 1959). Also, pruning is expensive. If dwarf mistletoe control requires severe pruning of a tree, there should be a good reason for not removing it.

If the DMR of a stand is greater than 3.0, dwarf mistletoe becomes a major factor affecting treatment decisions. The objective should be to use methods that minimize abrupt impacts on scenic and other values. Five possible solutions to problems created by heavy infestations are available:

1. Leave immature patches and stands alone if (a) the mortality rate is not extreme, (b) partial cutting is not justified for reasons other than stand improvement, and (c) adjacent stands have no special values that require immediate protection. At Manitou, several small, severely infected patches surrounded by large treated areas of lower density were left undisturbed to serve as wildlife cover. They were isolated from adjacent healthy trees by cutting enough diseased trees to leave strips 50 ft wide. The infected patches will be treated after nearby areas have become dense enough to be attractive to wildlife.

2. Thin immature patches and stands if reduced density is needed to improve scenic or other values. No direct benefits to timber production or improvement in stand quality can be expected.

3. Apply a shelterwood seed cut to infected mature trees still capable of producing seed, but without a pine understory. Since each potential seed producer must have a DMR of 3.0 or less, seed trees may be hard to find in heavily infested stands. Schedule shelterwood removal before the new stand is more than 3 ft tall or 10 years old.

4. Apply a shelterwood final cut where mature trees occur over an acceptable understory of younger pines. Thin and prune the young stand, with emphasis on reducing the dwarf mistletoe infestation in the former understory.

5. Clearcut small areas if the stand is breaking up and other solutions are not applicable. Make the boundaries of the cleared areas irregular to minimize impact on the landscape. Regeneration is obtained from natural seeding or planting, depending on width of the cleared area and condition of adjacent stands. None of the cleared area should be more than about 150 ft from an acceptable seed tree if natural regeneration is desired. Heavy infestations of dwarf mistletoe are confined to ridges on the Manitou Experimental Forest. In similar situations, it may be appropriate to manage part of the area of cleared upper south slopes for browse production.

[7] *Personal communication with David R. Patton, Principal Wildlife Biologist, Rocky Mountain Forest and Range Experiment Station, Forest Hydrology Laboratory, Tempe, Arizona.*

It is sometimes possible to reduce the number of trees cut for dwarf mistletoe control without increasing the danger of infecting adjacent trees and stands. Bole infections where the stem is larger than 5 inches in diameter are of low vigor and produce few dwarf mistletoe seeds (Mark and Hawksworth 1974). Such infections therefore are unlikely sources of additional infection and the tree may be left, if needed, to meet scenic or other objectives.

Other Damaging Agencies

In addition to dwarf mistletoe, ponderosa pine is subject to other damaging agencies of varying importance in the Montane Zone. Some of these are:

1. Mountain pine beetle—A major pest that lowers scenic values, kills landscape trees on homesites, and reduces the yield of wood products. The possibility of reducing the area of new infestation through control of stand density was mentioned in a previous section. Post-treatment stand densities should be sufficiently low that basal areas will not increase enough to exceed 150 ft^2 before the time of the next planned cut. The possibility of exceeding this level can be checked by producing a yield table for the stand in question, using actual initial stand values (Myers 1971, Myers et al. 1972). Cutting to control existing beetle infestations must be done outside the period of emergence, about July 15 to September 10 in the Montane Zone (McCambridge 1964). A forest pest control specialist should be consulted before control is undertaken.

2. Heart rots—For safety reasons, the presence and degree of infection by heart rots must be considered when selecting reserved trees along roads, in campgrounds, and other places where use by forest visitors is concentrated. Red rot, fortunately, is unimportant in the Montane Zone as compared to the Black Hills and the Southwest (Andrews 1971).

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Scientific Names of Species Mentioned

Abert's squirrel	*Sciurus aberti ferreus* True
Aspen	*Populus tremuloides* Michx.
Blue spruce	*Picea pungens* Engelm.
Douglas-fir	*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco
Dwarf mistletoe	*Arceuthobium vaginatum* subsp. *cryptopodum* (Engelm.) Hawksworth and Wiens
Flammulated owl	*Otus flammeolus* Kaup
Mountain chickadee	*Parus gambeli* Ridgway
Mountain pine beetle	*Dendroctonus ponderosae* Hopkins
Ponderosa pine	*Pinus ponderosa* Laws.
Red rot	*Polyporus anceps* Peck
Tree swallow	*Iridoprocne bicolor* Vieillot
Violet-green swallow	*Tachycineta thalassina* Swainson
Williamson's sapsucker	*Sphyrapicus thyroideus* Cassin
Willow	*Salix* spp.
Yellow-bellied sapsucker	*Sphyrapicus varius* L.

Myers, Clifford A.
1974. Multipurpose silviculture in ponderosa pine stands of the Montane Zone of central Colorado. USDA For. Serv. Res. Pap. RM-132, 15 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Presents silvicultural prescriptions for ponderosa pine in an area where several uses and products of the forest are important but scenic and recreation values predominate. Although far from virgin condition, the pine stands now bear little resemblance to a managed, regulated forest. Present diversity within and between vegetative types can and should be maintained.

Keywords: Forest cutting systems, *Pinus ponderosa*, silviculture, stand condition, thinning (trees), timber management.

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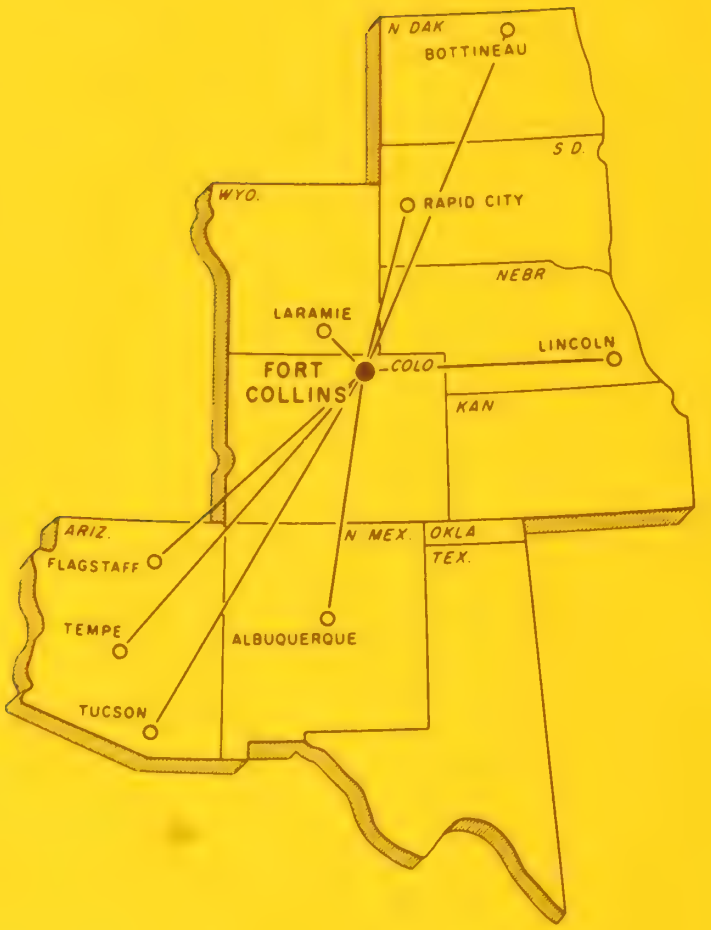
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